A HIGH INTENSITY GAMMA RADIATION SURVEY METER

JEROME HENRY KING, JR.

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by

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B.E., Yale University
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A system using no batteries or other power-supply, in which a phosphor is viewed by a photo-voltaic cell of the barrier-layer type is shown to be too insensitive with presently available components to give meter indications in the radiation range of interest.

Visual observation of the luminescent response of a Zn-CdS phosphor is shown to permit detection of gamma radiation at less than 0.020 r/hr and measurement at less than 0.4 r/hr. The upper limit has not been explored but is shown to be above 100 r/hr. Two meter designs based on visual comparison of the brightness of a detector phosphor with that of a standard light source have been developed. One of these requires no power supply, the standard light source being a phosphor disc excited by a long-lived beta emitter, tests of which are described. The advantage in reliability of the device over an

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electronic circuit is evident.

Measurements of brightness comparison at 0.8 r/hr showed standard deviations of 12% for each of two observers with 7% difference in the means of their readings. Dark adaptation of the observer, for a period varying inversely with radiation intensity, is required below about 15 r/hr.

Methods are described for preparing phosphor screens of any desired thickness by binding the phosphor powder in transparent plastics. In lucite, the greatest light yield under gamma excitation was obtained at 1.0 gm/cm^2 of Zn-CdS, with an optimum phosphor to plastic weight ratio of 2.8:1. With polystyrene, the light yield of a given weight of phosphor in the optimum phosphor-plastic ratio is shown to be 30% higher than that of the same thickness of phosphor alone, a result of the relatively high index of refraction of the polystyrene. The light yield as a function of thickness of Zn-CdS and Zn_2SiO_4 powder under gamma and beta excitation, and of various phosphor-plastic mixtures under gamma excitation are shown. For these measurements a procedure was devised to calibrate the response of a photomultiplier to the brightness of a luminescing phosphor in units of foot-lamberts.

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CHAPTER 1

NEED FOR A HIGH-INTENSITY GAMMA RADIATION SURVEY METER

The possibility of the use of atomic weapons against densely populated areas as well as strictly military targets has created a need for the wide-spread distribution of radiation dosage rate monitoring and survey instruments for use by radiological defense teams, and by individual persons, both civilian and military. Until very recently such instruments have been designed primarily for use by trained personnel under conditions such that personnel hazards due to failure of an instrument could be minimized by careful handling and maintenance, and by the provision of more than one monitor if necessary. Low cost and simplicity of operation have not been essential factors in the design of such instruments and, whether portable or laboratory types, they have in general been characterized by high sensitivity and the precision required for research purposes.

In this chapter we consider briefly the conditions under which individual persons and radiological defense teams might require instruments for measuring radiation, examine current civil defense specifications for such instruments, and mention the currently available instruments that might fall within the scope of these specifications.

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1.1. Radiation after Atomic Weapon Attack.

At this writing, the most useful, if not the only available, source of unclassified information on the radiation to be expected after an atomic weapon attack is a publication, "The Effects of Atomic Weapons," (L1)[1] which reflects the experience obtained by the United States with the experimental and wartime nuclear explosions up to the beginning of 1950. We summarize some of the pertinent comments contained therein, quoting freely to avoid ambiguities.

Atomic weapons fall into two categories, explosives and the spread of radioactive contaminants (the latter is known as radiological warfare).

The effects of explosions vary depending on the relation of the burst to the surface of the ground or water, and this discussion is sub-divided accordingly. The figures quoted below apply to a "nominal" atomic bomb, equivalent to 20,000 tons of TNT, and we confine consideration to the residual radiation resulting from the weapon, excluding the initial burst of electro-magnetic and particle radiation which is substantially completed within one minute after the explosion. In general it can be said of the residual radiation that the personnel hazards arise primarily from gamma rays, and secondarily from beta-rays, the other forms of radiation

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(a) High air burst (above 500 feet):

> "....if an atomic bomb is detonated at a high altitude, so as to cause maximum blast damage in a city, the hazard due to radioactivity on the ground after the explosion is small." (p. 269).

(b) Low air burst (below 500 feet):

Approximate radiation dosage rates were measured on the ground one hour after the first nuclear explosion at Alamogordo in 1945, where the burst occurred at a height of 100 feet. The dosage rate was 8,000 roentgens per hour at ground zero (the point directly under the burst), and fell off rapidly with (horizontal) distance from ground zero, to 10 r/hr at 1500 feet and to 0.3 r/hr, at 3000 feet. (p. 270).

> "....after an air burst at low altitude an area, small compared with the damage area due to the bomb, near the explosion center would be uninhabitable because of the radiation hazard....It would probably be 6 hours or more before it would be safe to walk across the area...." (p. 270).

In addition to the residual radiation on the ground under the burst, separate consideration is given, in the case of low bursts, to "fall-out," that is, particles of dust carried upward

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> "The fall-out in the case of a low air burst might be an inconvenience but it would not, in general, represent a real danger. It would probably rarely be enough to prevent passage across an area, although it might necessitate suspension of operations for a few days within the area." (p. 274).

(c) Surface Explosion:

> "It is reasonably certain that the contamination due to neutron-induced activity in the vicinity of the explosion would be very high....airborne activity, which could produce a significant fall-out, might constitute a serious hazard in areas directly downwind at some distance from the explosion." (pp. 274, 275).

(d) Underwater Burst:

> "Of the types of atomic explosion the underwater test at Bikini produced by far the greatest degree of radioactive contamination... The extent and degree of contamination will probably vary markedly with the conditions, such as.... depth of the burst, meteorological conditions.... and topography." (pp. 276-277).

Of the total radiation dosage at a given distance from surface zero, about 90% may be expected within 30 minutes of the explosion. Integrated dosage contours, based on the Bikini underwater burst, where a 5 m.p.h. wind was blowing, place the 100 roentgen (total dose) contour 3.3 miles downwind from the burst, and the 400 r contour 2.2 miles from the burst. In

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Approximate dosage rates one hour after the burst, downwind, were 50 r/hr at 2 miles, 10 r/hr at 3 miles and at 5 miles the radiation was negligible. A different wind velocity or a shift in the wind shortly after the explosion could of course alter the results considerably.

(e) Radiological Warfare:

> "On the whole it may be concluded that if radiological warfare is used as a weapon, it will be in the form of emitters of penetrating gamma radiation for which protective clothing and gas masks would be ineffective... However, it would appear to be a difficult matter to lay down such a concentration of gamma emitters over a large area as would cause serious injury from a short exposure."(p.288)

1.2. Monitoring Equipment for Emergency Workers.

While the foregoing comments establish the almost self-evident fact that an atomic attack on a city would result in radioactive contamination affecting a large number of people, they do not readily lead to the particular limits of sensitivity and other specifications for an instrument intended for emergency use.

For guidance in these matters we turn to a recent publication of the Federal Civil Defense Administration (F2) which sets forth specifications for radiological monitoring instruments for use in general civil defense operations. These specifications were compiled by a committee, including repre-

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> (2) A low-intensity instrument for special long-range survey work in the weeks following an attack..... The range of these instruments need not exceed 500 milliroentgens per hour.
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The low-intensity instrument[2] currently recommended by the Federal Civil Defense Administration is an ionization-chamber type, portable, battery-powered device having five ranges of full-scale readings 5, 50, 500, 5000 and 50,000 milliroentgens per hour, detecting gamma radiation of energy 80 Kev up to 1.5 Mev. Specified precision is ± 15% (of the 4/5 full scale reading). It meets military requirements for ruggedness, resistance to temperature, humidity and pressure changes. Battery life provides 1000 hours of continuous operation and a shelf-life of about 1 year at 70°F.

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Specifications for a Civil Defense High-Intensity Radiation Survey Meter," published by the Federal Civil Defense Administration in the same report (F2). The specifications "establish performance requirements for a small, lightweight, rugged field instrument for measuring gamma radiation which may result from atomic disaster. The instrument will be used by relatively inexperienced personnel and should provide ease of operation, maximum operating life and require a minimum of maintenance." These specifications, then, provide the best currently available guide to the characteristics of an instrument for emergency use and they will be briefly outlined.

The device may be based on any practicable detection principle and must respond to gamma radiation of 0.08 to 1.5 Mev energy, over the range 0.025 to 500 roentgens per hour, reading correctly within ± 30% at 5, 50, and 500 r/hr. An integral calibration device is to be provided to check performance at one scale reading. Battery life is to provide 25 hours of continuous operation, and overall life except batteries must be at least 500 hours at 500 r/hr. There are in addition strict requirements to cover various operating conditions, as temperature, humidity, corrosion, immersion and vibration effects. The instrument is to be portable, having a weight of less than five pounds and a volume of less than 100 cubic inches. Various requirements on circuit stability, internal construction and external features are also specified.

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The device may be based on any practicable detection principle and must respond to gamma radiation of 0.06 to 1.5 Mev energy, over the range 0.025 to 500 roentgens per hour, reading correctly within ± 30% at 5, 50, and 500 r/hr. An integral calibration device is to be provided to check performance at one scale reading. Battery life is to provide 25 hours of continuous operation, and overall life except batteries must be at least 500 hours at 500 r/hr. There are in addition strict requirements to cover various operating conditions, as temperature, humidity, corrosion, immersion and vibration effects. The instrument is to be portable, having a weight of less than five pounds and a volume of less than 100 cubic inches. Various requirements on circuit stability, internal construction and external features are also specified.

Because of the relatively recent publication of these specifications, it is doubtful that any currently available radiation meter has been designed specifically to meet them. Two devices whose sensitivity range may possibly be extended to meet the above specifications have become available in recent months and will be described briefly.

LeVine and DiGiovanni (L6) have described a compact hand-held instrument detecting gamma rays by a Geiger-Muller tube using 700 volts provided by a novel vibration circuit operating from two small (Type D) dry cells. Two models have been designed, one covering the range 0.2 to 500 r/hr, the other about 0.02 to 5 r/hr. The unit cost, for parts only, of either of these is $14.50 if 100,000 are to be manufactured. The authors state that modifications can be made to meet the above specifications.

Another recent instrument, the "Pocket Radiac" (T1) is an ionization chamber type reading 0 to 25 r/hr on a logarithmic scale, with stated accuracy of $\pm$ 25% at any reading. The instrument responds to gamma rays of greater than 0.1 Mev energy and to beta-rays of over 1.0 Mev. Operating life is 85 hours, from two hearing-aid type batteries. A model reading up to 500 r/hr is in preparation. The present model is about the size of a man's hand. Cost is $49.50 in small quantity.

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tives of the sort of instrument contemplated by the specifications quoted above. A number of other types of gamma-ray detectors have been mentioned as potentially useful after an atomic explosion, for measuring the integrated dose received by an individual. These include pocket dosimeters of the electroscope or ionization chamber type, photographic film badges, and recently a silver-activated phosphate glass which fluoresces under ultra-violet light in proportion to the total gamma radiation to which it has been subjected. All of these are quite simple and rugged, but require auxiliary apparatus for either reading or re-charging (where applicable) or both. Though a measure of the dosage rate can be obtained with all of them by timing the exposure of the device, their use for this purpose in the field is subject to the principal objection that the information so obtained applies to the past, not the present, and that careful shielding is required to maintain the usefulness of any reserve stock of such devices in the presence of radiation.

We conclude from this brief survey that in spite of the many varieties of gamma-ray measuring instruments in existence, there remains an unfilled need for a wide-range gamma radiation survey meter of simple and rugged characteristics. It is the purpose of this paper to describe some initial investigations of two possible bases for such a device.

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CHAPTER 2

PHOSPHOR VIEWED BY PHOTO-VOLTAIC CELL

2.1. Introduction.

In the search for a principle upon which an instrument of the sort described in Section 1.2 might be based, attention was directed first to the use of a simple photo-voltaic cell, of the barrier-layer type.[1] The cell was to view a phosphor crystal excited to luminescence by gamma rays or other energetic radiation and the sensitive surface of the cell would convert the light into an electric current, measured by a micro-ammeter. Preliminary calculations, reproduced below, indicated that the maximum current obtainable would be quite small, but nevertheless it seemed advisable to experiment with this principle to an extent sufficient to determine the possible sensitivity of such a device made with currently available components. It is apparent that, should sufficient sensitivity be achieved, a device of this nature would be extremely simple, readily manufactured, and would have an indefinitely long shelf-life, since no power supply would be required.

2.2. Choice of Photo-Voltaic Cell.

Barrier-layer photo-voltaic cells now commercially

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CHAPTER X

THEORETICAL STUDY OF PHOTO-VOLTAIC CELL

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available are practically all of the selenium type (Z1), consisting of a thin layer of crystalline selenium on an iron base, covered with a thin sputtered metal electrode. Selenium is thought to be a defect semi-conductor with holes in its highest filled energy band (Z1). In contact with iron, of lower work function, some of the holes are filled by electrons migrating across the interface from iron to selenium, setting up a field across the boundary region which forms the barrier layer. In this condition, electrons excited by incident light may rise to the empty conduction band. In the interior of the semi-conductor, such electrons have a short lifetime, as they fall into the holes of the highest filled energy band, and no current will flow. In the region of the barrier layer, however, these holes are filled by the electrons which migrated from iron. Hence electrons in the conduction band have a longer lifetime during which they are urged by the field toward the iron, creating a current. Under moderate illumination, the open-circuit potential difference between the iron base and the top electrode is of the order of 0.2 volts, rising to a maximum of about 0.55 volts at very high illumination levels (V1).

Inspection of manufacturers' literature indicates that the performance characteristics of photo-voltaic cells

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Inspection of manufacturers' literature indicates that the performance characteristics of photo-voltaic cells

vary but little from one manufacturer to the next. Some of the characteristics of a typical General Electric cell of 1.1 in.^{2} sensitive surface are shown in Figures 2.2-1, 2, and 3, and an equivalent circuit representing conventional cells is given in Figure 2.2-4. Major characteristics of interest here are:

(a) Spectral sensitivity maximum nearly coincides with the wavelength of maximum sensitivity of the human eye (Figure 2.2-1).

(b) With small external resistance loads, current output is proportional to the illumination (Figure 2.2-2).

(c) Internal resistance (and hence optimum external load) is a function of illumination (Figure 2.2-3).

(d) Short-circuit current is nearly proportional to sensitive area. Open circuit voltage is practically independent of area (G1).

(e) Special attention to the details of manufacture may produce cells with current response about 10% higher than the average (G1).

(f) Representative values of the equivalent circuit elements of Figure 2.2-4 are (Z1):

$C \approx 0.1$ to 0.5 mfd.

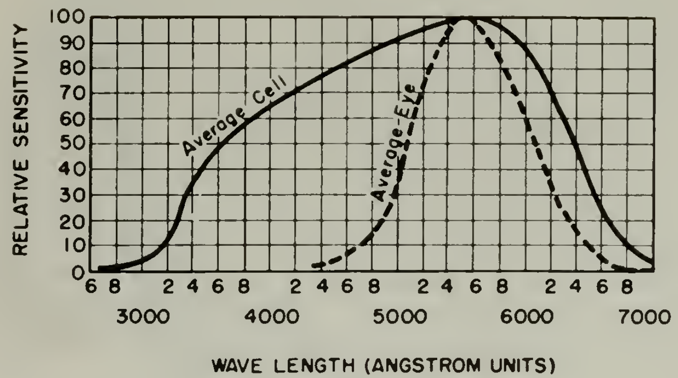

Figure 2.2-1. Photocell spectral sensitivity for constant energy at each wavelength. (From Ref. G1.)

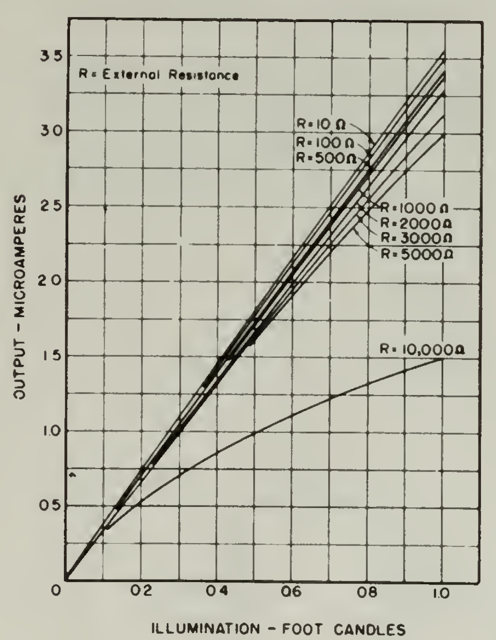

Figure 2.2-2. Photocell current vs. illumination (tungsten, 2700°K) (From Ref. G1.)

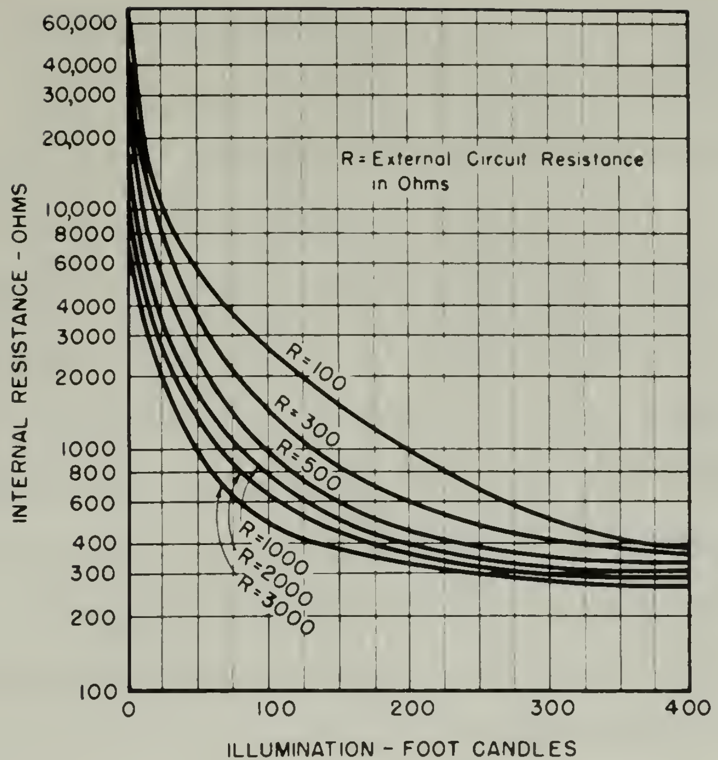

Figure 2.2-3. Photocell internal resistance vs. illumination (tungsten, 2700°K). (From Ref. G1.)

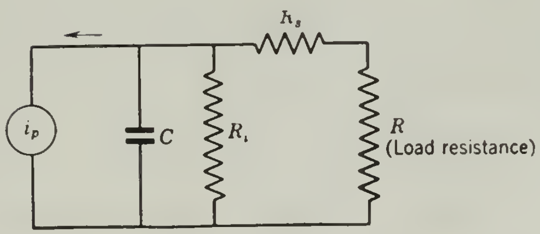

Figure 2.2-4. Photocell equivalent circuit. (From Ref. Z1.)

$R_s \approx$ 50 ohms

R_i = a function of illumination and external circuit resistance as shown in Figure 2.2-3.

With these characteristics in mind, two specially made photocells with sensitive areas of 15 cm^2 were obtained (from General Electric Company) for use in the experiments described below. For these cells the characteristics as given in Figures 2.2-1, 2, and 3 represent minimum expected performance. (If small external loads are used, corresponding to short-circuit conditions, the currents shown in Figure 2.2-2 should be multiplied by the ratio of the areas ($\frac{2.3}{1.1}$ = 2.1) to give the expected current.)

2.3. Choice of Luminescent Material.

Having selected a photo-voltaic cell, we sought a luminescent material (phosphor) with maximum sensitivity to gamma radiation. In addition to availability and cost, these major factors were considered:

(a) The material chosen should be of high atomic number, so that it will absorb as much energy as possible from the gamma radiation.

(b) The material should emit as visible light a large fraction of the energy absorbed.

(c) The emitted light should fall as nearly as

possible in the region of maximum photocell sensitivity.

(d) Since the response of photo-voltaic cells decreases with increasing frequency, rapid decay of the emitted light pulses would be undesirable.

Kallman and co-workers (K1) have made an extensive study of the absolute energy yield of various luminescent materials excited with alpha particles, gamma rays, and weak x-rays. Their results show that, in general, the inorganic phosphors emit as visible light a greater fraction of the energy absorbed than do the organic luminescent materials. Of the inorganic materials they tested under gamma radiation from radium and its decay products, the two most suitable for the present purpose are copper-activated zinc sulfide (denoted ZnS(Cu)) with an efficiency of 22%, and copper-activated zinc-cadmium sulfide (Zn-CdS(Cu)), with an efficiency of 18%. These efficiency data represent the ratio of energy emitted as light to the (radium) gamma radiation energy absorbed by a thin layer of phosphor. The efficiencies of several sulfide phosphors, including these two, have been shown (K4), (K1), to be a function of the intensity of the exciting radiation, and of temperature. For this reason Kallman (K2) has stated, referring to the efficiencies cited above, that they may be in error by as much as 1/5 to 1/3,

possible in the region of maximum photocell sensitivity.

(d) Since the response of photomultiplier cells decreases with increasing frequency, rapid decay of the emitted light pulses would be undesirable.

Kallmann and co-workers (81) have made an extensive study of the absolute energy yield of various luminescent materials excited with alpha particles, gamma rays, and beta rays. Their results show that, in general, the inorganic phosphors emit as visible light a greater fraction of the energy absorbed than do the organic luminescent materials. Of the inorganic materials they tested under gamma radiation from radium and its decay products, the two most suitable for the present purpose are copper-activated zinc sulfide (denoted ZnS(Cu)) with an efficiency of 23%, and copper-activated zinc-cadmium sulfide (Zn-CdS(Cu)), with an efficiency of 18%. These efficiency data represent the ratio of energy emitted as light to the (radium) gamma radiation energy absorbed by a thin layer of phosphor. The efficiencies of several sulfide phosphors, including those two, have been shown (44), (81), to be a function of the intensity of the exciting radiation, and of temperature. For this reason Kallmann (81) has stated, referring to the efficiencies cited above, that they may be in error by as much as 1/5 to 1/3.

though the relative values are correct.

Both of these phosphors emit light in a fairly broad spectrum with the maximum in both cases falling near the wavelength of maximum sensitivity of the selenium barrier-layer photo-voltaic cell. If the relative spectral distribution, J_λ, of the energy emitted by a phosphor is known as a function of wavelength, then the average current sensitivity, S, of a photo-sensitive surface to this distribution can be calculated as:

$$S = \frac{\int_0^\infty J_\lambda S_\lambda d\lambda}{\int_0^\infty J_\lambda d\lambda} \leq 1,$$

where S_λ represents the current response of the photo-sensitive surface at wavelength λ, relative to the current output I_0 (amperes per unit incident energy) at the wavelength of maximum sensitivity. S is thus a figure of merit for various combinations of photocell surfaces and phosphors. Calculations of S have been made for the two phosphors mentioned above as being most suitable, based on the response curve S_λ for the General Electric cell (Figure 2.2-1). For ZnS(Cu), the spectral emission curve of a very efficient phosphor prepared by Dubs (23) was employed, while for Zn-CdS(Cu), a spectral emission curve, Figure 3.2-1, for one

of the plastic-phosphor discs described in Chapter 4 was used. The ordinates of these curves represent, in arbitrary units, energy emitted per unit energy absorbed, per unit wavelength, under excitation by ultra-violet radiation. Since the emission spectrum of a given phosphor is constant, or nearly so, under various modes (alpha, beta, gamma, ultra-violet) of excitation (L3), and (K1), these data may be used for the present problem involving gamma-ray excitation.

The figures obtained for S by graphical integration are:

ZnS(Cu) : S = 0.89

Zn-CdS(Cu) : S = 0.95

The time rate of decay of light pulses from phosphors appears to be a sensitive function of constitution and method of preparation of the phosphor. Much conflicting data are found in the literature on this topic. However there is no doubt that ZnS(Cu) and Zn-CdS(Cu) emit light in very long pulses compared to the short (of the order of 10^{-7} seconds) pulses of the organic phosphors, and the zinc and cadmium sulfides are for this reason almost invariably used where long persistence of luminescence is desired, e.g., in slow-moving oscillography (R3), (L2). The phosphorescent decay of a Zn-CdS(Cu) phosphor material used in the present experiments

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The figures obtained for E by graphical integration are:

ZnS(Cu) : E = 0.89

Zn-CdS(Cu) : E = 0.95

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persisted for more than 20 minutes after excitation was removed.

To summarize, ZnS(Cu) and Zn-CdS(Cu) appear to be suitable phosphors for the present application, as they have reasonably high gamma-ray absorption characteristics, are among the most efficient energy converters, emit light in a band favoring the selenium photo-sensitive surface, and emit pulses of long duration which avoid the poor high-frequency response of barrier-layer cells.

2.4. Estimate of Sensitivity.

Attempts to calculate the expected sensitivity of a simple phosphor-photovoltaic cell-ammeter arrangement suffer from the scarcity of data on the performance of photovoltaic cells at the very low levels of illumination expected from the phosphor under moderate gamma irradiation. The data in Figure 2.2-2 are the best available on commercial cells at illumination levels below 1 foot-candle (1 lumen/ft.^{2}). However, the lowest portion of these curves, below about 0.2 foot-candles, is an extrapolation (W1). On the basis of the brief discussion of the theory of the photovoltaic cell given above, a linear relationship between illumination and current response, passing through the origin of coordinates, seems plausible. If the illumination is small, so that the field at the selenium-iron interface is not disturbed by a large current flow, then a fixed fraction

persisted for more than 20 minutes after excitation was removed.

To summarize, ZnS(Cu) and Zn-CdS(Cu) appear to be suitable phosphors for the present application, as they have reasonably high gamma-ray absorption characteristics, are among the most efficient energy converters, emit light in a band favoring the selenium photo-sensitive surface, and emit pulses of long duration which avoid the poor high-frequency response of barrier-layer cells.

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of the photoelectrons should move from the selenium to iron under the influence of the field. For a given spectral distribution of the incident light, the linear relationship should extend down to zero illumination because, of course, the photo-electric threshold cannot depend on the rate at which photons strike the surface, but only on the energy per photon. We conclude that the data of Figure 2.2-2 can be used at least as an order-of-magnitude guide at the lowest illumination levels.

We may now summarize the process by which the energy of gamma radiation is to be converted into a meter indication in the phosphor-photovoltaic cell-ammeter circuit, by tracing the energy through the system. For the materials ($Z \leq 48$) and gamma-ray energies (average 0.7 Mev (11)) of interest here, the photoelectric effect and pair production may be neglected in comparison to the Compton effect, so that the absorption of gamma-ray energy is proportional to the mass of the absorber (11). Since one roentgen represents the absorption of 5.24×10^7 Mev per gram of air (12), we have as the rate of energy absorption by one gram of phosphor from one roentgen per hour:

$$5.24 \times 10^7 \ \frac{\text{Mev}}{\text{hr.}} \times 1.6 \times 10^{-13} \ \frac{\text{joule}}{\text{Mev}} \times \frac{1}{3600} \ \frac{\text{hr}}{\text{sec}}$$

$$= 2.3 \times 10^{-9} \text{ watts.}$$

of the photoelectrons should come from the emission to iron under the influence of the field. For a given spectral distribution of the incident light, the linear relationship should extend down to zero illumination because, of course, the photoelectric threshold cannot depend on the rate at which photons strike the surface, but only on the energy per photon. We conclude that the data of Figure 4.2-3 are the result of at least an order-of-magnitude error at the lowest illumination levels.

We may now summarize the process by which the energy of gamma radiation is to be converted into a usable collection in the phosphor-photovoltaic self-powered circuit, by tracing the energy through the system. For the materials (p. 48) and gamma-ray energies (reference 2.9 and (11)) of interest here, the photoelectric effect and pair production may be neglected in comparison to the Compton effect, so that the absorption of gamma-ray energy is proportional to the mass of the absorber (11). Since one roentgen represents the absorption of 5.24×10^7 Mev per gram of air (11), we have as the rate of energy absorption by one gram of phosphor from one roentgen per hour:

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$$= 2.3 \times 10^{-9} \text{ watts}$$

The efficiency with which the phosphor converts this power into light, (paragraph 2.3), is 0.18 for Zn-CdS. The fraction of emitted light reaching a sensitive cell surface can approach unity if we use a thin phosphor disc between two cells of the same surface area and shape as the phosphor. However for this example we shall use a single cell for which, with a thin phosphor, this fraction might be about 0.4. The relative sensitivity of the photocells for the incident light spectrum was calculated in paragraph 2.3 above as 0.95 for Zn-CdS.

Thus far we have traced the energy to the point where it produces output current from the photocells, which we may now write as:

$$i = 2.3 \times 10^{-9} \left(\frac{\text{watts absorbed}}{(\text{r/hr})\text{- gram}}\right) \times 0.18 \left(\frac{\text{watts emitted}}{\text{watts absorbed}}\right)$$

$$\times\, 0.4 \times 0.95 \times I_o \left(\frac{\text{amperes}}{\text{watt}}\right) = 1.6 \times 10^{-10}\, I_o$$

amperes/r/hr/gram phosphor,

where I_o is the response of the photocells in amperes per watt incident.

An approximate evaluation of I_o can be made by reference to Figure 2.3-2 where it is seen that the limiting slope at low illumination for the larger external resistances (for which power output is greatest) is approximately 3.2 micro-

amperes/foot-candle. The cell represented by the curve has an area of $(1.1/144) = 0.0076$ ft.^{2}, and 1 lumen of tungsten light at 2700° Kelvin is equivalent to about 0.0039 watts in the visible range, hence I_o becomes:

$$I_o = \frac{3.2 \times 10^{-6}}{0.0039 \times 0.0076} = 0.11 \text{ amperes/ watt incident.}$$

Thus we arrive at an estimated photocell current of

$$i = 1.6 \times 10^{-10} \times 0.11 = 1.8 \times 10^{-11} \text{ amperes/r/hr/gram}$$

phosphor for the conditions stated. In view of the several approximations involved, this figure should be regarded only as an upper limit for the current. As such, we may calculate the minimum radiation measurable with the phosphor-cell-ammeter circuit. If 0.1 microampere is taken as the minimum current measurable with a readily portable moving-coil instrument, and assuming a phosphor of mass 10 grams, we could detect approximately:

$$\frac{10^{-7}}{1.8 \times 10^{-11} \times 10} = 550 \text{ roentgens per hour,}$$

an impractically large minimum for a portable instrument to be used for the monitoring of human exposure to radiation.

2.5. Experiments and Conclusions.

Despite these discouragingly large estimates some exploratory experiments were made. These will be briefly described:

(a) A large anthracene crystal of excellent quality, mass 175 grams, was placed on a General Electric PV-1 photovoltaic cell. Current output of the cell was read by a Leeds and Northrup galvanometer. The crystal was irradiated with a Co^{60} source (0.98 rhm) of gamma rays separated from the crystal only by two thicknesses of black cloth, such that the estimated gamma radiation on the crystal surface facing the cell was 400 roentgens per hour. A maximum current of 9×10^{-10} amperes was measured. (This result cannot be compared with the calculation of the preceding section because the emission spectrum of anthracene is widely different from that of the sulfide phosphors.)

(b) A phosphor consisting of 9.7 grams of Zn-CdS (Cu) dispersed in a polystyrene binder formed into a disc 3 mm. thick and 5 cm. in diameter was placed between two General Electric PV-2 photovoltaic cells (see last paragraph, Section

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(b) A phosphor consisting of 2.7 grams of ZnS-CdS (Cu) dispersed in a polystyrene binder formed into a disc 3 mm thick and 3 cm in diameter was placed between two General Electric PV-1 photovoltaic cells (see last paragraph. Section

2.2) connected in parallel, with output fed to a Beckman micro-microammeter. The phosphor was irradiated by the same Co^{60} source used above, such that the average radiation over the faces of the phosphor disc was greater than 500 roentgens per hour. Average current reading was 2×10^{-10} amperes, or

$$\frac{2 \times 10^{-10}}{10 \times 500} = 4 \times 10^{-14} \text{ amperes/r/hr/gram}$$

phosphor, so that the estimate of maximum current in Section 2.4 is too high by a factor of greater than 10^3.

We conclude that the simple phosphor-photovoltaic cell-ammeter circuit cannot at present form the basis for a practical radiation meter requiring no source of energy other than the energy of the gamma radiation measured. Several schemes have come to mind or have been suggested by others for improving the sensitivity of the device. One example is the n-layer sandwich, each layer consisting of cell-phosphor-cell. If these were connected in series, then in principle, at least, the open-circuit voltage under small irradiation could be made as large as we pleased by making n very large. Or consider two concentric spheres, one much larger than the other. The interior of the larger sphere

would be coated with a good phosphor, and the exterior of the inner sphere would be divided into many small segments, each forming a separate photo-voltaic cell, again with all segments connected in series. If these or other similar schemes seem attractive, they lose much of their promise when we consider that a sensitivity improvement of at least 10^4 is required, and for this we probably would do better with one new high-sensitivity detector, than with a large number of photo-voltaic cells.

At this point in the work we shifted to the human eye as the detector, and no further experiments with photo-voltaic cells were undertaken.

CHAPTER 3

PHOSPHOR VIEWED BY THE EYE

3.1. Characteristics of the Eye.

The extraordinary sensitivity of the human eye can be appreciated by considering the energy flow in the form of luminous flux which can just be perceived by a completely dark-adapted eye. Varying estimates have been given of this quantity ([illegible]1), a conservative statement being (C1) that it is less than 10^{-16} watts, or, expressed in photons of light at the wavelength of maximum sensitivity of the eye, less than 300 elementary photons per second.

In order to take advantage of this sensitivity for visual detection and measurement of radiation, we must examine some other characteristics of the eye's response to light which will be discussed briefly as follows:

(a) Relative visibility and Purkinje effect.

(b) Contrast sensitivity variation.

(c) Change in light threshold during adaptation.

(d) Light and color thresholds.

(a) The familiar relative visibility curve for the light-adapted eye, in the form agreed upon by international convention ([illegible]2), appears as curve (a) in Figure 3.1-1. The sensitivity of the eye is relatively constant at ordinary

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SENSITIVITY OF THE EYE

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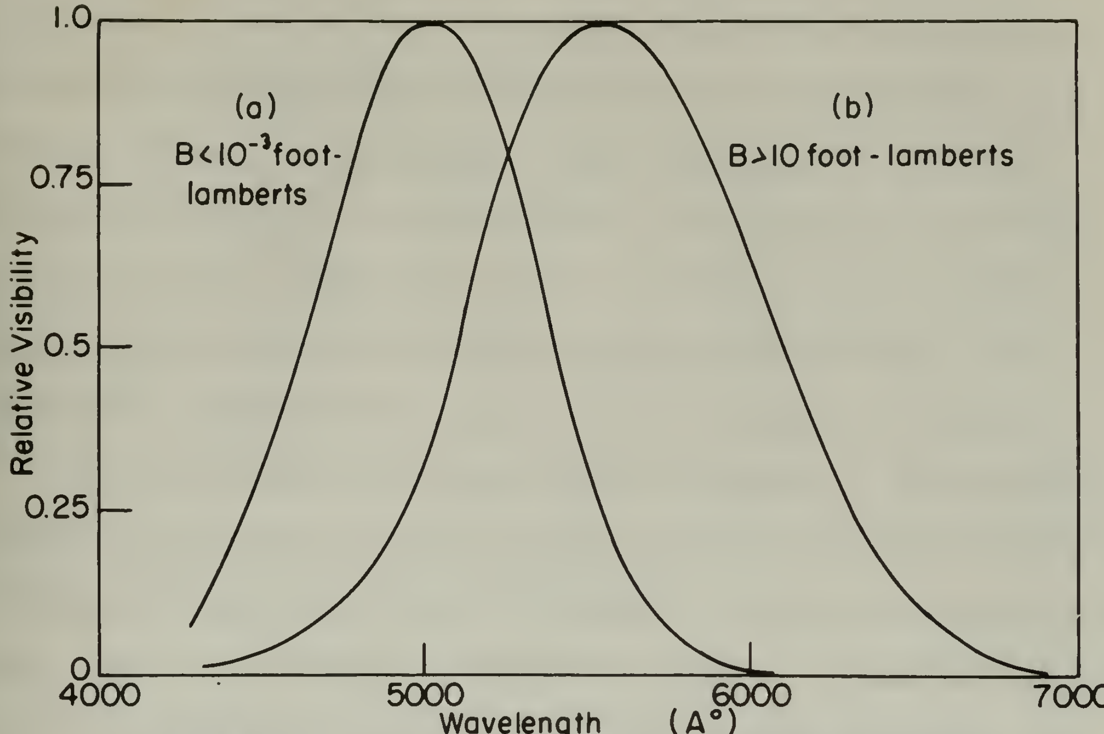

Figure 3.1-1 RELATIVE VISIBILITY CURVES (Walsh, W2)

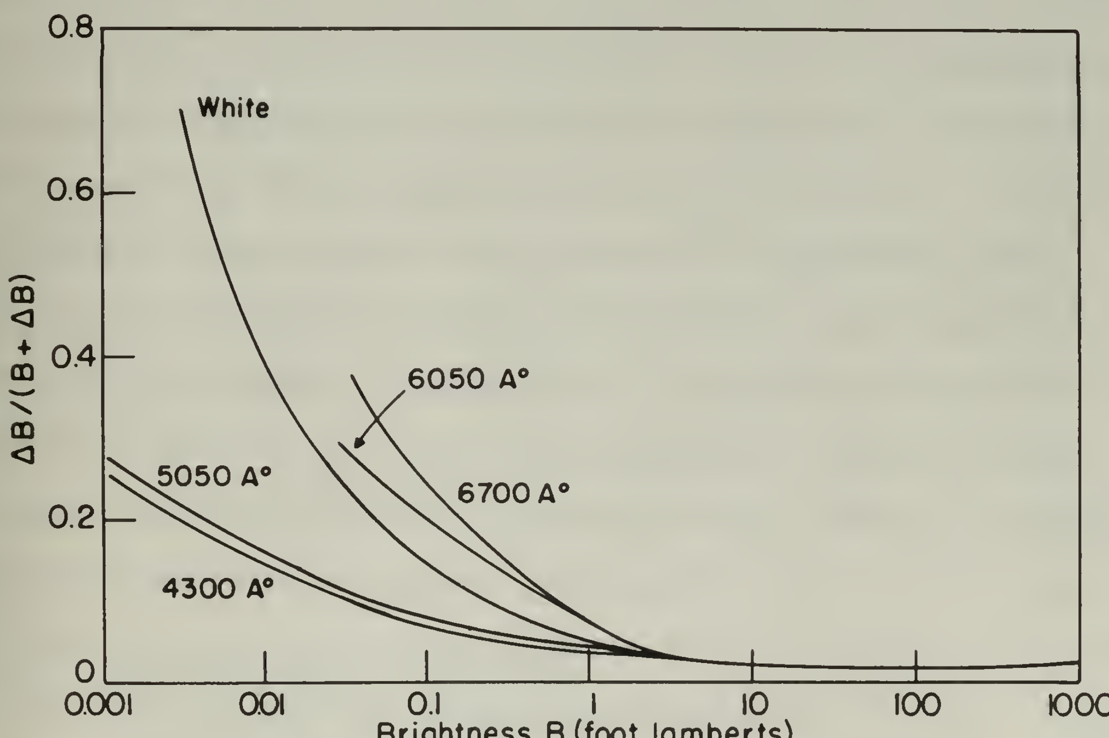

Figure 3.1-2 VARIATION OF PERCEPTIBLE CONTRAST WITH BRIGHTNESS (I.C.T., I I)

light levels, but as the adaptation brightness decreases, the visibility curve begins, at about 10 foot-lamberts, to shift to shorter wavelengths. This phenomenon, known as the Purkinje effect, is accompanied by a decrease in width of the curve, as indicated by (b) in Figure 3.1-1, which represents the visibility from brightnesses of less than about 10^{-3} foot-lamberts down to the threshold of vision.

(b) The fractional brightness difference, or contrast, $\Delta B/(B + \Delta B)$, between two surfaces, which can just be perceived, is shown in Figure 3.1-2 as a function of field brightness and color (W2). It is noted that at the higher levels of illumination, the perceptible brightness difference is small and nearly constant for all colors, but increases as field brightness decreases, and that the Purkinje effect is manifested in an earlier widening of the perceptible brightness difference for the red end of the spectrum than for the blue. Two further facts which are not indicated in the figure are that the ability to distinguish brightness difference, especially at low light levels, is improved by a reduction in angular field of view (W2) and that the perceptible contrasts indicated in Figure 3.1-2 can be reduced, at any color or brightness, by a practiced observer judging the mean of the points of first appearance of inequality in each direction. Walsh (W2) states that the average of many readings taken in this way has been found to improve contrast perception by a factor

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of 8, under favorable conditions.

(c) The gradual improvement in sensitivity of the eye after illumination has been greatly reduced is illustrated by Figure 3.1-3, from (S1). (The ordinate of this curve is the logarithm of the reciprocal of the threshold brightness at the time indicated.) It is interesting to note that, although dark adaptation is essentially complete after 40 minutes, some increase in sensitivity has been reported after as long as 16 hours of adaptation (S1).

(d) Figure 3.1-4 presents the color and light thresholds (W2) plotted as functions of wavelength. In the red, recognition of color and the perception of light both vanish at very nearly the same retinal illumination, but as wavelength decreases, it is possible to perceive light at illumination levels much lower than those required for color recognition, in the region of the so-called twilight vision. (The unit of brightness used in this curve is the photon, equal to the illumination of the retina of the eye, when the pupillary aperture is one square millimeter, by an object having a brightness of one candle per square meter, or 0.292 foot-lamberts.)

3.2. The Visual Radiation Meter.

(a) Principle of operation.

In 1911, Lord Rutherford (R5) utilized the lumi-

light levels, but at the comparable brightness appearance, of 5, under favorable conditions.

(e) The gradual improvement in sensitivity of the eye after illumination has been greatly reduced is illustrated by figure 3.1-3, from (11). (The ordinate of this curve is the logarithm of the reciprocal of the threshold brightness at the time indicated.) It is interesting to note that, although dark adaptation is essentially complete after 30 minutes, some increase in sensitivity has been reported after as long as 16 hours of adaptation (11).

(f) Figure 3.1-4 presents the color and light threshold data (3) plotted as functions of wavelength. In the red, recognition of color and the perception of light both require at very nearly the same retinal illumination, but as wavelength decreases, it is possible to perceive light at illumination levels much lower than those required for color perception, in the region of the so-called twilight vision. (The unit of brightness used in this curve is the photon, equal to the illumination of the retina of the eye, when the pupillary aperture is one square millimeter, by an object having a brightness of one candle per square meter, or 0.292 foot-lamberts.)

3.2. The Visual Acuity Factor

(a) Principle of operation.

In 1911, Abel Robertson (12) outlined the lumi-

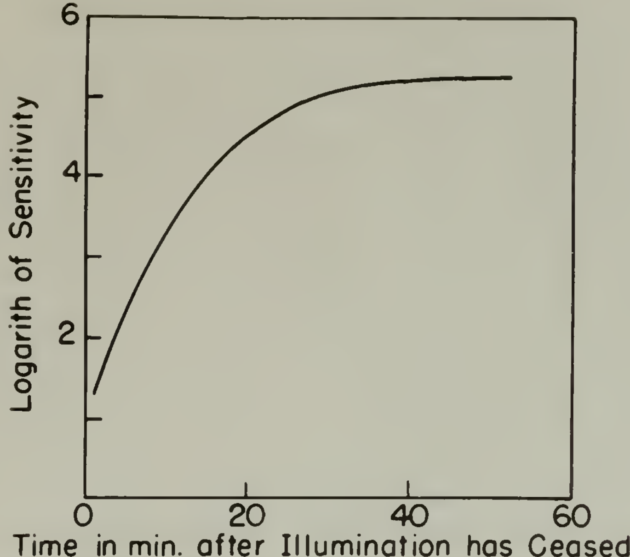

Figure 3.1-3 RISE OF SENSITIVITY OF THE RETINA WITH CONTINUED DARK-ADAPTATION OF THE EYE. (Southall, S1)

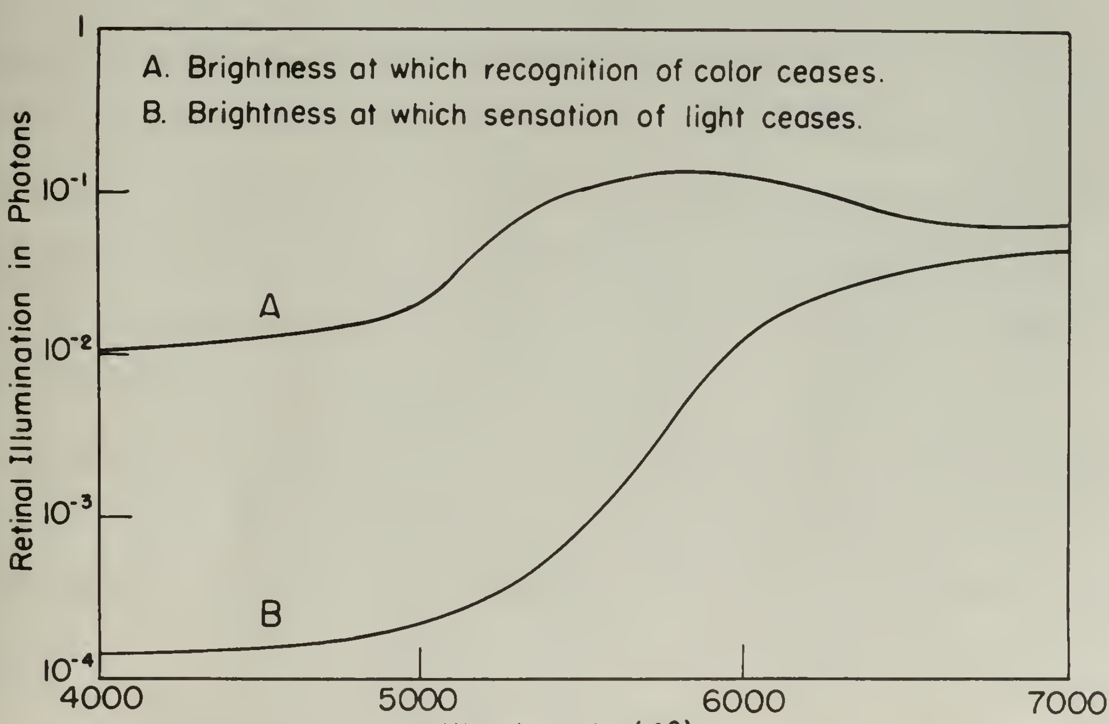

Figure 3.1-4 EXTINCTION OF LIGHT AND COLOR (Walsh, W2)

nescense of a zinc sulfide screen for visual detection of nuclear radiation in his classic experiments on alpha-ray scattering. The device proposed and developed in the present work rests on the same principle used by Rutherford, but we are primarily interested in the detection and quantitative measurement of gamma radiation, rather than counting individual alpha particles. To accomplish this, we introduce a standard light source of variable brightness, with which the zinc sulfide (or other phosphor) screen, excited to luminescence by the gamma radiation to be measured, is compared. The act of adjusting the intensity of the standard light source to obtain a brightness match then serves to measure the gamma radiation. The lever, dial, or other means by which the standard source is adjusted can be calibrated directly in roentgens per hour. It is important to note that we have here a dosage rate meter, not an integrating dosimeter, and that, if practical, it would certainly constitute one of the simplest rate meters for gamma radiation yet devised. We proceed therefore to examine the design criteria and practicality of such a device, to consider some of the possible variations, and to demonstrate the characteristics and performance of one form of the complete instrument.

(b) <u>Choice of Phosphor.</u>

Turning first to the luminescent material, or

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(b) Choice of Phosphor.

Turning first to the luminescent material, or

phosphor, it is apparent that maximum sensitivity will be attained if we choose a phosphor with a high efficiency for the conversion of gamma radiation into light, with as much as possible of the emitted light falling in the wavelength band where the eye has maximum sensitivity. But for the Purkinje effect, choice of a phosphor for visual observation could be considered as a problem identical with choosing a phosphor to be viewed by a photo-voltaic cell (Section 2.3). However, we now wish to find an efficient energy converter whose spectral emission maximum falls at the same wavelength as the peak sensitivity of the eye, at the brightness levels expected from the radiation to be measured.

We calculate the order of magnitude of the surface brightness of a thin phosphor disc 1 1/2 inches in diameter, containing 10 grams of phosphor of efficiency 0.2, excited by, say, 0.1 roentgens per hour. Using the calculation of Section 2.4, that the power absorbed by 1 gram of phosphor from 1 roentgen per hour is approximately 2.3×10^{-9} watts, we find this brightness to be:

$$2.3 \times 10^{-9} \frac{\text{watts}}{\text{gram - r/hr}} \times 10 \text{ grams} \times 0.1 \text{ r/hr} \times 0.2$$

$$\frac{\text{watts emitted}}{\text{watts absorbed}} \times \frac{621 \text{ lumens/watt}}{\frac{1.75}{144} \text{ ft.}^2} \times \frac{1}{2}$$

or:

$$B = 1.2 \times 10^{-5} \text{ lumens/ft}^2.$$

In this calculation we have neglected emission from the edge of the disc, total internal reflection, and absorption of the emitted light by interior phosphor crystals, and have assumed that all the light is emitted at the wavelength of maximum sensitivity of the eye. If the emitting surface is perfectly diffuse, we may express this brightness as the same number of foot-lamberts. We note from curve (b) of Figure 3.1-1 that at this brightness the wavelength of maximum sensitivity of the eye is about 5040 Angstrom units, so that we seek a phosphor whose emission peak is at this same wavelength. Furthermore, for best results, the emitted light should have a spectral distribution no broader than the visibility curve at this brightness.

Selection of a commercially available phosphor on the basis of a specified shape and placement of its emission curve is not readily accomplished particularly when only a small amount is desired. The characteristics of a particular shipment of luminescent material are not necessarily identical to those of the preceding shipment, and the manufacturers are not ordinarily willing to guarantee their product in this respect. After inspection of several compilations of phosphor characteristics, those published by Leverenz (12-15) being

most valuable, two phosphors were obtained whose spectral emission bands were in the desired region: Zn-CdS(Cu)[1], and Zn_2SiO_4(Mn)[2], the former being, according to Kallman (K1), more than twice as efficient as the latter, and this was borne out by the results obtained here. For use in the visual radiation meter these phosphors, obtained in the form of powder, were mixed with a plastic binder, molded into discs of convenient size, and tested for efficiency, as described in detail in Chapter 4. Tests under gamma-ray excitation, described in Section 3.3, show that for Zn-CdS(Cu), the brightness calculation above is of the correct order of magnitude.

Spectral distribution curves for each of these phosphor materials, formed into discs with lucite, were obtained from an automatic-recording, grating spectrograph under unfiltered ultra-violet excitation. These results are shown in Figures 3.2-1 and 3.2-2. The emission curve for Zn-CdS (Cu) follows very closely the shape of the threshold visibility curve, but peaks at a wavelength of 5275 Angstrom units, somewhat higher than was desired. Nevertheless, the overlap between the Zn-CdS curve and the threshold curve in-

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1. Type B phosphor, Patterson Screen Division, E.I. DuPont de Nemours Co. Towanda, Pa.

2. Type 33-[illegible]-2[illegible] phosphor, Tube Parts Department, Radio Corporation of America, Harrison, N.J.

most valuable, two phosphors were obtained whose spectral emission bands were in the desired region: Zn-CdS(Cu)[1], and $Zn_2SiO_4(Mn)$[2], the former being, according to [illegible] ([illegible]), more than twice as efficient as the latter, and this was borne out by the results obtained here. For use in the visual radiation meter these phosphors, obtained in the form of powder, were mixed with a plastic binder, molded into discs of convenient size, and tested for efficiency, as described in detail in Chapter 4. Tests under gamma-ray excitation, described in section 7.3, show that for Zn-CdS(Cu), the brightness calculation above is of the correct order of magnitude.

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1. Type B phosphor, Fluorescent Screen Division, E.I. duPont de Nemours Co., Towanda, Pa.

2. Type [illegible]-21 phosphor, Tube Parts Department, Radio Corporation of America, Harrison, N.J.

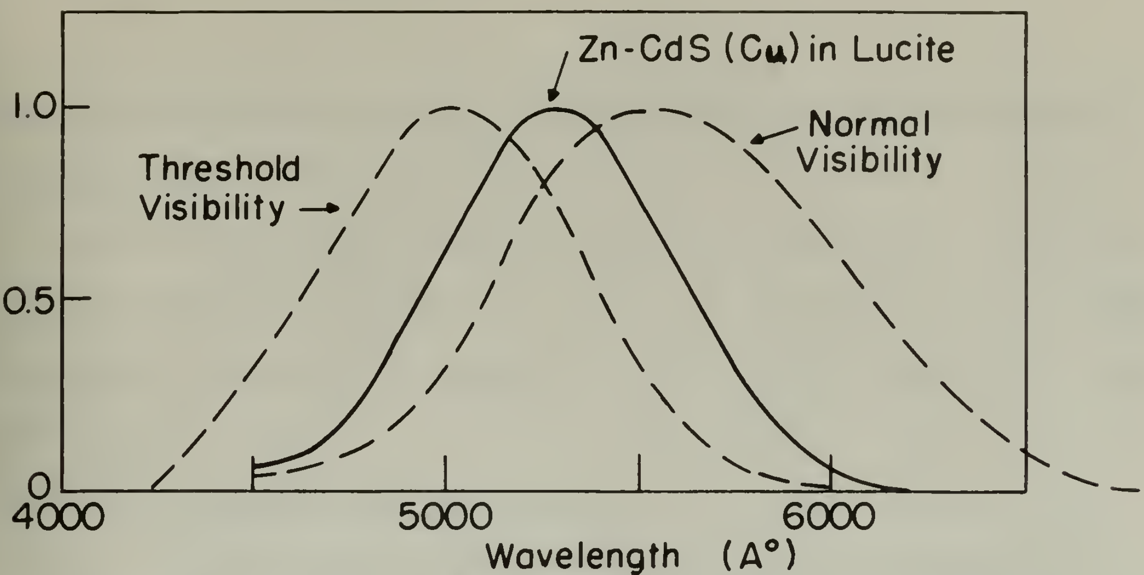

Figure 3.2-1 SPECTRAL DISTRIBUTION OF EMISSION FROM Zn-CdS (Cu) IN LUCITE COMPARED WITH NORMAL AND THRESHOLD VISIBILITY CURVES.

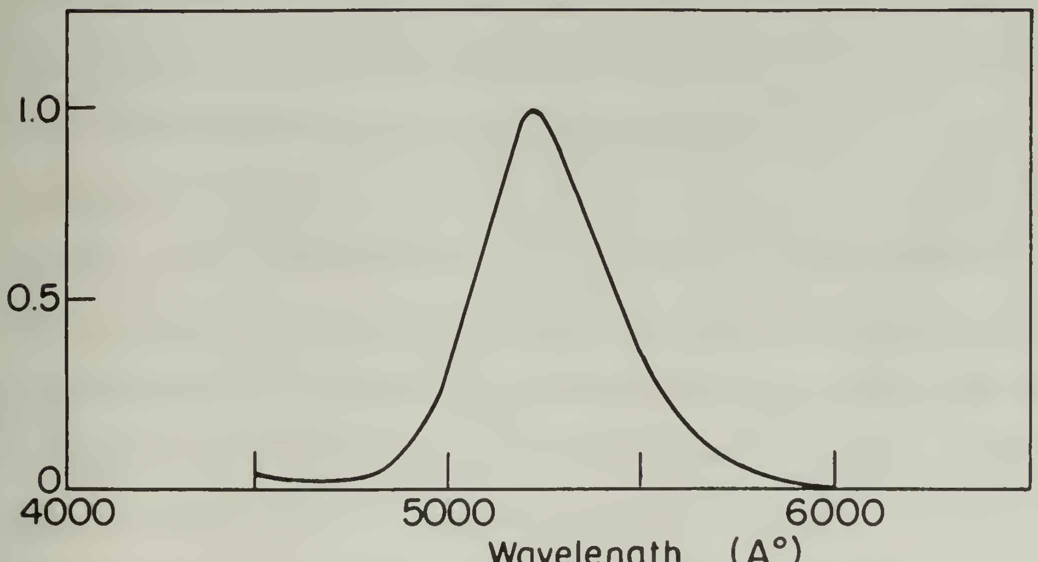

Figure 3.2-2 SPECTRAL DISTRIBUTION OF EMISSION FROM Zn_2SiO_4 (Mn) IN LUCITE

dicates that this phosphor would be fairly satisfactory for our purpose.

The Zn_2SiO_4(Mn) emission spectrum peaks at a slightly shorter wavelength (5210 A°), and has essentially the desired shape, but, as will be seen, its total light emission is much inferior.

(c) Standard Light Source.

In order to avoid uncertainties introduced by the Purkinje effect into the task of matching the brightness of two surfaces of different color, we require that the standard light be identical in spectral distribution with that of the detector phosphor. The standard source, of course, could consist of a battery-powered light bulb, suitably filtered, but this arrangement is objectionable in the present application because of battery shelf-life (and active life), and because color temperature complications arise if the intensity of the emitted light is varied by adjusting filament current. The latter can be avoided by other methods of varying intensity but the batteries remain. We therefore consider the possibility of using a phosphor excited by a source of radioactivity, built into the instrument, as the comparison light source.

The source of excitation energy for such a phosphor should have a half-value period of several years, and if, for

comparison purposes, the standard light source is to be mounted close to the detector phosphor, the former should not emit penetrating radiation which would cause luminescence of the latter. Thus we eliminate from consideration the radium and thorium series, because of their gamma components, and polonium (low gamma emission) because of its short life (139 days). In fact, the standard tabulations of the radio-active nuclides (S3), and (S4), reveal no alpha emitters which meet our specifications. Several beta-ray sources emitting no gamma rays are available in quantity from the Isotopes Division of the Atomic Energy Commission (A1) or from distributors. Of these, strontium-90 is among the least expensive and the available energy per disintegration from this nuclide is comparatively large. Sr^{90}, a fission-product daughter of two very short-lived beta-ray emitters, decays (F1) according to the scheme:

$$Sr^{90} \xrightarrow[19.9\text{ years}]{\beta^{-}\,0.6\text{ Mev}} Y^{90} \xrightarrow[\sim 62\text{ hours}]{\beta^{-}\,2.3\text{ Mev}} Zr^{90}\ \text{(stable)}.$$

Hence, when secular equilibrium has been attained, each decay of a Sr^{90} nucleus yields two beta particles, with an average energy release of about 0.9 Mev per disintegration.

The extensive literature on phosphors includes very few precise data on the brightness obtainable from self-excited phosphors, and none at all has been located on the

possible deterioration of luminescence in such a phosphor as a result of constant bombardment of the phosphor crystal structure by beta-rays. That this last point may be of importance in the present problem is illustrated by the decay with time of the luminescence from the self-luminous paints on watch and instrument dials, signs, etc., most of which are excited by radiation from radium or mesothorium. The destructive effect of the radioactivity on the phosphor can, at least, be listed as a variable influencing the light output from a radio-active light source, the effect of which may be comparable with the effect of the half-life of the radio-active exciter.

The brightness of a copper-activated, green-emitting zinc sulfide screen (of unspecified thickness but presumably comparable to the range of radium alpha particles in ZnS, about 5 mg/cm^2) under alpha-ray excitation has been measured by Blau and Feuer (B2). They coated a plate with 1 microgram of radium per square centimeter and placed it 4 millimeters from a phosphor screen in an evacuated chamber, obtaining a screen brightness of 1 to 2 micro-lamberts (0.001 to 0.002 foot-lamberts approximately) for use as a standard light source. Boardman and Dawson (B4) report brightnesses of up to 22.5 micro-lamberts from an intimate mixture of zinc sulfide with an alpha-emitting radio-active salt (otherwise unidentified).

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The brightness of a copper-activated, green-emitting zinc sulfide screen (of unspecified thickness but presumably comparable to the range of radium alpha particles in zinc, about 5 mg/cm^2) under alpha-ray excitation has been measured by Kuhn and Feuer (82). They coated a plate with 1 microgram of radium per square centimeter and placed it 4 millimeters from a phosphor screen in an evacuated chamber, obtaining a screen brightness of 1 to 2 micro-lamberts (0.001 to 0.002 foot-lamberts approximately) for use as a standard light source. Hurdman and Dawson (84) report brightnesses of up to 22.5 micro-lamberts from an intimate mixture of zinc sulfide with an alpha-emitting radio-active salt (otherwise unidentified).

Since both of these results were based on alpha excitation of the phosphor, whereas the present application requires gamma-free beta ray excitation, it becomes necessary to demonstrate that a usable brightness could be attained with a beta source.

Sr^{90} in chloride solution, as obtained from the Atomic Energy Commission,[3] was precipitated as a carbonate by the addition of excess ammonium carbonate. The precipitate was permitted to stand for 24 hours, then filtered. The filter paper, carrying the $Sr^{90}CO_3$ precipitate was cemented onto an aluminum disc 1 inch in diameter, and the active deposit, well distributed over an area 3/4 inches in diameter, was protected by a thin (1.5 mg/cm^2) aluminum foil. This disc was then mounted on a rod screwed into the back face of the disc for convenience in handling. The source so obtained had an activity, as measured by an ionization chamber comparison against a source of known activity, of 0.5 (± 0.1) millicuries.

A phosphor made of 1.00 gram of Patterson Type B zinc-cadmium sulfide (copper activated) and molded by means of 0.50 grams of a lucite binder into a disc 1 7/16 inches in diameter and 0.05 inches thick, was placed on the source

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3. Unusual care must be taken in work with Sr^{90}, for its long half-life, the energetic beta-ray from its daughter yttrium, and the fact that it appears to be a bone-seeker make it unusually toxic among beta emitters. The latest (January 1, 1951) recommendation of the International Commission on Radiological Protection (T2) is that the maximum permissible amount of strontium-90 in the body is 1.0 microcurie.

Since both of these results were based on alpha excitation of the phosphor, whereas the present application requires excitation by beta radiation, it became necessary to demonstrate that a usable brightness could be attained with a beta source.

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A phosphor cake of 1.00 gram of Patterson Type D zinc-cadmium sulfide (copper activated) and molded by means of 0.50 grams of a lucite binder into a disc 1 7/16 inches in diameter and 0.03 inches thick, was placed on the source

---

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disc and the brightness of the phosphor measured with the Taylor Low-Brightness Meter, with the result, from a series of 7 measurements, of 1.74 ($\pm$ 0.05) x 10^{-3} foot-lamberts. To reduce this brightness to familiar terms, it was noted that the phosphor's glow was detectable immediately when placed in the shadow under a desk or chair in a brightly lighted room.

From the brightness calculation above, for the gamma-irradiated detector phosphor, this brightness would be equivalent to gamma radiation producing approximately:

$$\frac{1.7 \times 10^{-3}}{1.2 \times 10^{-5}} \times 0.1 = 14 \text{ roentgens per hour}$$

which would thus be the upper detection limit for a meter using this particular beta source and comparison phosphor.

To increase the brightness of the standard or comparison phosphor, we may increase the source strength or make more efficient use of a given source activity. There appears to be no reason why the beta-source could not be mixed directly with the phosphor material and molded into a thin disc with plastic. Alternatively, activation of the completed phosphor-plastic disc by neutron bombardment in a reactor might be feasible, provided a suitable nucleus (such as beryllium) were included in the plastic or phosphor. If the active material were obtained with high specific activity,

disc and the brightness of the phosphor measured with the Taylor low-brightness meter, with the result, from a series of 7 measurements, of 1.74 (± 0.05) x 10^{-7} foot-lamberts. To reduce this brightness to familiar terms, it was noted that the phosphor's glow was detectable immediately when placed in the shadow under a desk or chair in a brightly lighted room.

From the brightness calculation above, for the gamma-irradiated detector phosphor, this brightness would be equivalent to gamma radiation producing approximately

$$\frac{1.7 \times 10^{-7}}{1.2 \times 10^{-6}} \cong 0.14 \text{ roentgens per hour}$$

which would then be the upper detection limit for a meter using this particular beta source and comparison phosphor.

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its presence in the phosphor-plastic mixture should not interfere significantly with the surface brightness of a thin phosphor. Of course such a procedure has the disadvantage that phosphor bombardment by the nuclear emission particles, with consequent possible destructive effect, is continuous, whereas with the source and phosphor separated, an absorber could readily be inserted when the meter is not in use. The manufacture of self-excited phosphors was not undertaken during this work because of the undesirability of contaminating the only available high-pressure lucite mold.

(d) Description of the Complete Meter.

Figures 3.2-3 and 4 are sketches of two of the many possible forms of the visual radiation meter. The sketches are self-explanatory, and a few comments on components not elsewhere mentioned will suffice.

The adjustment for a brightness match between a detector phosphor and the standard light source can readily be made with crossed polarizers (Figure 3.2-3). One type that appears to be satisfactory[4] is obtainable in the form of thin sheets which are easily mounted. Two such sheets have a transmission with optical axes parallel of 21%, and effect a reduction by a factor of 200 when the axes are crossed. If three such sheets are used, the center one

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4. Type HN-32, Polaroid Corporation, Cambridge, Mass. The transmission data herein were furnished by the manufacturer.

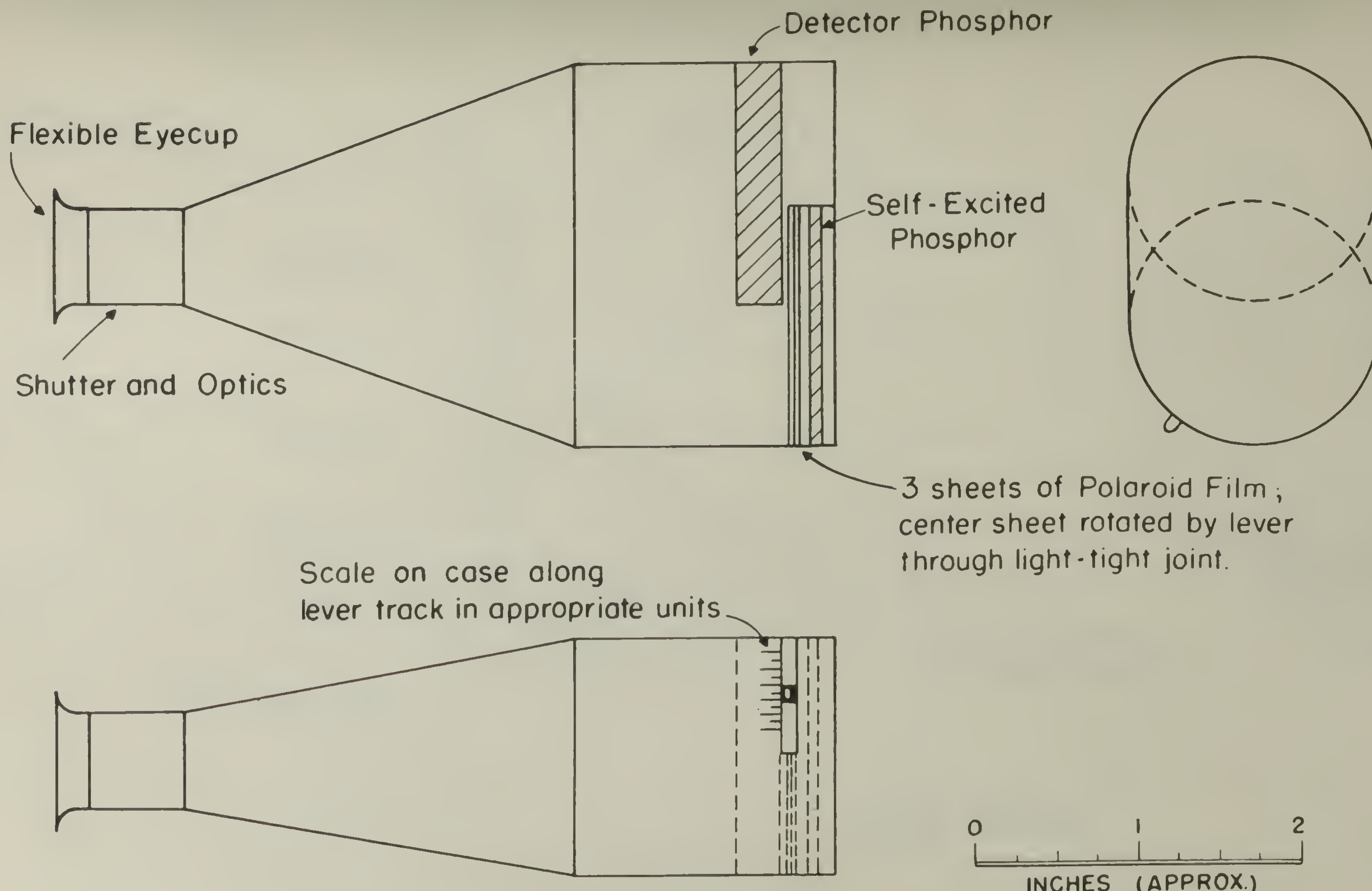

Figure 3.2-3 SELF-EXCITED PHOSPHOR MODEL OF THE VISUAL RADIATION METER

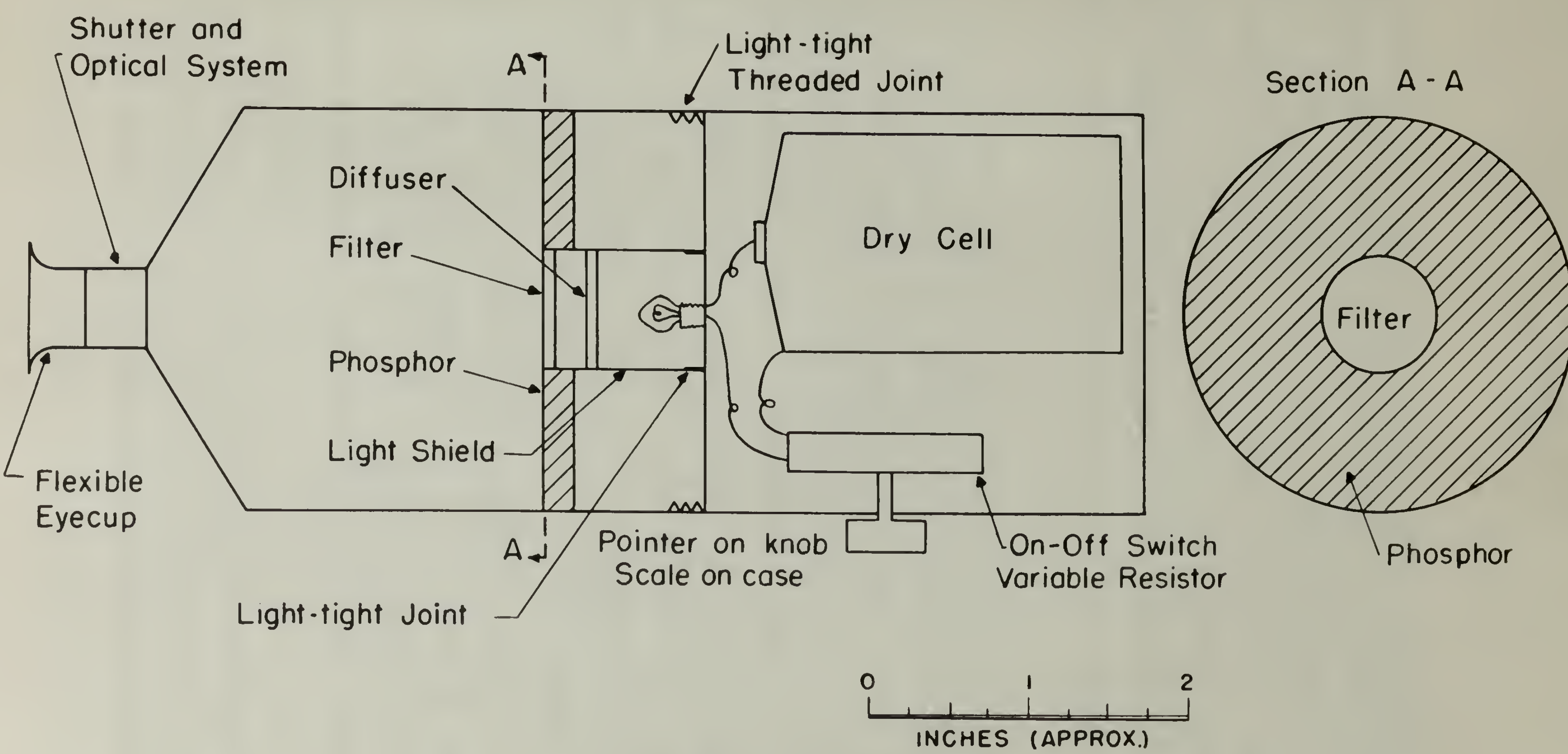

Figure 3.2-4 BATTERY-POWERED MODEL OF THE VISUAL RADIATION METER

being rotated while the other two are fixed, as shown in the figure, the open transmission is 13%, the maximum attenuation being a factor of 40,000. The transmission of this material is reduced, as the axes are rotated, quite uniformly in the region of the emission of zinc-cadmium sulfide (Figure 3.2-1), though there is a non-uniformity in the high and low wavelength regions of the visible spectrum.

The design of Figure 3.2-4 employs for simplicity a rheostat for adjusting the intensity of the standard lamp. As a result, the filter can correct the light to the spectral distribution of the phosphor emission over a narrow range of intensities, only. At very low brightness, in the domain of twilight (colorless) vision, this effect could be compensated by adjustment of the scale calibration, but at high intensities it would bring in the uncertainty of matching two surfaces of different colors. If this should be found to increase the overall error significantly, the intensity of the standard light should be adjusted by polaroids or an optical wedge, and an ammeter should be included in the circuit so that a fixed current could be maintained through the filament.

The optical system for viewing the two surfaces need be no more elaborate than a glass or plastic plate to exclude dust. In the case of the model using a beta-source to pro-

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The optical system for viewing the two surfaces need be no more elaborate than a glass or plastic plate to exclude dust. In the case of the model using a beta-source to pro-

duce the standard light, the lens should be thick enough to shield the eye from the radiation. A shutter of some kind is necessary at the eyepiece because of the long phosphorescent decay of the sulfide phosphors after exposure to sunlight; a simple cap fitting over the eyepiece might be sufficient.

A number of variations on the general principle of visual observation of a phosphor for radiation measurement are possible. One of the simplest consists of a phosphor viewed through a series of openings of varying opacity in an opaque disc or strip. The openings could be in the form of numerals, a number code giving the approximate radiation dosage rate corresponding to the lowest number which could just be perceived. Such a device, with no standard for comparison, would, however, yield varying results depending on the degree of dark adaptation of the observer.

3.3. Tests of the Visual Radiation Meter.

(a) Brightness Standard.

The Taylor Low-Brightness meter (LBM) consists of a long (60 cm) open cylinder through which an observer views an illuminated circular area silhouetted against a circular field of the surface toward which the instrument is aimed, whose brightness is to be measured. The illuminated area, actually elliptical in shape, is a magnesium carbonate surface which reflects into the observer's eye

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3.3. Tests of the Visual Radiation Meter.

(a) Brightness Standard.

The Taylor low-brightness meter (TLBM) consists of a long (60 cm) open cylinder through which an observer views an illuminated circular area silhouetted against a circular field of the surface toward which the instrument is aimed, whose brightness is to be measured. The illuminated area, actually elliptical in shape, is a magnesium carbonate surface which reflects into the observer's eye

light emitted by a standard lamp through an aperture in the side of the main cylinder. The intensity of the standard light source is adjustable by filters and an optical wedge, so that by comparison of the circle, illuminated by the standard, with the external field of view, brightness can be measured over the range from 10^{-1} to 10^{-5} foot-lamberts. The standard lamp bulb operates at constant current, so that color changes do not accompany intensity, or brightness, changes of the reflecting surface. The instrument was calibrated by the manufacturer (General Electric Co.) just prior to its use in the present experiments, but no low-brightness standards were available for re-checking during the course of the work.

It is apparent, from this description of the LBM, that when it is used to measure the brightness of a phosphor luminescing under the excitation of gamma radiation, it becomes essentially a visual radiation meter similar to the form sketched in Figure 3.2-4. Use of the LBM in this way is subject to several limitations. The standard light source, a tungsten filament, has a color distribution far different from the essentially blue-green of the phosphor, so that at the higher radiation levels it is necessary to match green and pale yellow brightnesses. The most serious fault of this arrangement arises from the 60 centimeter length of the

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LEM which forces placement of the phosphor so far from the eye that the field of view of the observer is not filled by the phosphor image, which subtends a cone of half-angle only 2°-24' when a 2-inch phosphor is used, and of 1°-49' with a 1 1/2-inch phosphor. Thus the threshold for detection of radiation with a given phosphor at the end of the LEM is much less than it would be for a smaller phosphor-to-eye distance.

(b) Detection Threshold, and Reproducibility of Measurements.

The minimum radiation which can be detected visually with the phosphors available, and the effect of distance between eye and phosphor were established by the following experiment. A phosphor disc 5 cm. in diameter was mounted at the end of a tube of the same inside diameter, 66 cm. long, with a black arrow-shaped figure 2 cm. long affixed to the face of the phosphor. Measurements were made of the maximum distance of a radium gamma source from the phosphor at which a dark-adapted observer could (a) determine without question the presence or absence of visible light from the phosphor, and (b) determine within 30° the angular orientation of the arrow. This procedure was then repeated with a tube 22 cm. long. The results, in terms of distance and roentgens per hour from the source (46.8 mgm. radium source, calibrated by the Bureau of Standards), calculated by the inverse square law, are given in Table 3.3-1.

LSM which forces placement of the phosphor so far from the eye that the field of view of the observer is not filled by the phosphor image, which subtends a cone of half-angle only 2°-26' when a 2-inch phosphor is used, and of 1°-49' with a 1 1/2-inch phosphor. Thus the threshold for detection of radiation with a given phosphor at the end of the LSM is much less than it would be for a smaller phosphor-to-eye distance.

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TABLE 3.3-1

Detection Threshold, and Effect of Phosphor-to-Eye Distance.

(46.8 mgm radium source - 45.4 mrhm.)

Phosphor-to-eye distance (cm).	Observation	Maximum source-to-phosphor distance (cm), and minimum roentgens per hour.			
		Observer F		Observer K	
		Cm	r/hr	Cm	r/hr
66	Detection Threshold	70	0.093	70	0.093
66	Arrow Orientation	25	0.727	20	1.13
22	Detection threshold	180	0.014	165	0.017
22	Arrow Orientation	70	0.093	60	0.126

This experiment demonstrates that the minimum detectable gamma radiation with this phosphor material is less than 20 mr/hr under favorable conditions. Some rough experiments with phosphor-to-eye distances indicate that the optimum may be less than 22 cm, for a 5 cm diameter phosphor. Further investigation of this point might produce evidence for an even lower detection threshold than shown above.

TABLE 5.5-1

Detection Threshold, and Effects of Phosphor-to-Eye Distance.

(46.0 mgm radium source = 45.4 mrhm.)

Phosphor-to-eye distance (cm).	Observation	Maximum source-to-phosphor distance (cm), and minimum roentgens per hour.			
		Observer P		Observer K	
		Cm	r/hr	Cm	r/hr
55	Detection Threshold	70	0.093	70	0.093
55	Arrow Orientation	25	0.727	20	1.13
22	Detection threshold	100	0.014	165	0.017
22	Arrow Orientation	70	0.093	60	0.126

This experiment demonstrates that the minimum detectable gamma radiation with this phosphor material is less than 20 mr/hr under favorable conditions. Some rough experiments with phosphor-to-eye distances indicate that the optimum may be less than 22 cm, for a 5 cm diameter phosphor. Further investigation of this point might produce evidence for an even lower detection threshold than shown above.

It is evident from Table 3.3-1 that the three-fold reduction of the distance from which the phosphor was viewed brought about a six-fold improvement in threshold sensitivity, and an eight-fold decrease in the minimum radiation required for arrow orientation. In view of this result, measurements made with the Low-Brightness Meter used as a visual radiation meter can be regarded only as a gauge of the reproducibility of brightness readings at very low light levels. Since the LBM was the only available comparison device for the low light levels, and since no way could be found to use a shorter eye to phosphor distance without major alteration of the instrument, it was used for this purpose in the next experiment to be described.

Two observers with no prior knowledge of the Low-Brightness Meter and no significant experience in photometry were used in this experiment. Both had uncorrected visual acuity in both eyes of 20/20, or better, with normal color perception, and had sufficient knowledge of the use and effects of gamma radiation so that it can be assumed that no psychological effects on this account perturbed the measurements. The observers were dark-adapted for at least fifteen minutes in a red adaption brightness of less than 10^{-2} foot-lamberts. The detector phosphor (Zn-CdS(Cu) in lucite) was 1 1/2 inches in diameter, viewed through the LBM so that it was 60 cm from the observer's eye. The phosphor

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was irradiated by a 10 mgm (8.1 mrhm) radium source, from the distances (phosphor to source) shown in Table 3.3-2. Each observer was permitted about 10 minutes familiarization with the arrangement before the readings shown in the table were taken.

TABLE 3.3-2

Brightness Measurements by Inexperienced Observers

(10 mgm radium source, 8.1 mrhm. Brightness in 10^{-6} foot-lamberts)

Distance phosphor to source:		9 cm.	10 cm.
Observer D		35	12.8
		31	19.6
		18	26.5
		23	35
	Mean	26.7	23.5
	Standard Deviation	9%	12%
Observer L		26	25
		31	31
		27.5	27
		27.0	18
	Mean	27.9	25.2
	Standard Deviation	5%	12%

was irradiated by a 10 mgm (6.1 urhm) radium source, from the distances (phosphor to source) shown in Table 4.3-2. Each observer was permitted about 10 minutes familiarization with the arrangement before the readings shown in the table were taken.

TABLE 4.3-2

Brightness Measurements by Inexperienced Observers

(10 mgm radium source, 6.1 urhm. Brightness in 10^{-6} foot-lamberts)

Distance phosphor to source:	9 cm.	10 cm.
Observer O	35	12.8
	31	19.6
	18	20.5
	21	35
Mean	26.7	23.5
Standard Deviation	9%	13%
Observer L	26	25
	31	21
	27.5	37
	27.0	15
Mean	27.9	25.2
Standard Deviation	5%	12%

For comparison, Table 3.3-3 shows reading taken by two relatively experienced observers, both of whom had handled and used the instrument on two previous occasions. Experimental conditions were the same as described above except that the phosphor was excited by ultra-violet light and a larger range of brightness was covered. These observers likewise had uncorrected 20/20 or better vision and normal color perception.

As expected the reproducibility of brightness comparison readings by a single observer is far better than the perceptible brightness difference data of Figure 3.1-2, since we are using the halving method mentioned in Section 3.1(b). However the reproduction of the readings of one observer by another is less satisfactory. In Table 3.3-3 it is seen that observer S reads consistently higher than observer K by a fraction which increases as brightness decreases. Other experiments have shown the disagreement between these two observers is always in the same direction, and that the threshold of S is at a higher brightness, and radiation, than that of K. Similar relationships exist between the readings and thresholds of observers L and D (Table 3.3-2), the latter having the lower threshold. A mass of additional data would be required before generalizations along this line could be stated.

TABLE 3.3-3

Brightness Measurements by Experienced Observers

(Ultra-violet excitation. Brightness in foot-lamberts)

Run	A	B	C	D	E	F
Observer S	29×10^{-4}	12.0×10^{-4}	10.8×10^{-4}	35.5×10^{-5}	15.5×10^{-5}	15×10^{-6}
	29	21.3	12.5	45	14.2	19.5
	29.8	18.6	10.5	27	15.3	17.2
	30	20.7	12.2	51	17.7	
		12.7		46	14.0	
		29.0			13.1	
		18.7				
Mean	29.4×10^{-4}	19.0×10^{-4}	11.5×10^{-4}	14.9×10^{-5}	14.9×10^{-5}	17.2×10^{-6}
Standard Deviation	2%	14%	5%	12%	5%	9%
Observer K	28×10^{-4}	16.0×10^{-4}	9.0×10^{-4}	36×10^{-5}	9.5×10^{-5}	10.5×10^{-6}
	24	15.5	9.5	34	7.0	10.5
	28	18.0	12.0	34	12.0	14.0
	27	16.5	12.8	40	13.0	
			11.0	31	10.0	
				27	12.5	
Mean	26.7×10^{-4}	16.5×10^{-4}	10.9×10^{-4}	33.6×10^{-5}	10.6×10^{-5}	11.7×10^{-6}
Standard Deviation	4%	4%	7%	6%	9%	16%
Ratio S/K	1.10	1.15	1.06	1.21	1.40	1.47

TABLE 3.3-3

Brightness Measurements by Inexperienced Observers

(Ultra-violet excitation. Brightness in foot-Lamberts)

Run	A	B	C	D	E	F
Observer B	29×10^{-4}	12.0×10^{-4}	10.8×10^{-4}	35.5×10^{-5}	15.5×10^{-5}	15×10^{-6}
	29	21.3	12.5	45	14.2	19.5
	29.8	18.6	10.5	27	15.3	17.2
	30	20.7	12.2	51	17.7	
		12.7		46	14.0	
		29.0			13.1	
		18.7				
Mean	29.4×10^{-4}	19.0×10^{-4}	11.5×10^{-4}	14.9×10^{-5}	14.9×10^{-5}	17.2×10^{-6}
Standard Deviation	2%	14%	5%	12%	5%	9%
Observer K	28×10^{-4}	16.0×10^{-4}	9.0×10^{-4}	36×10^{-5}	9.5×10^{-5}	10.5×10^{-6}
	24	15.5	9.5	34	9.0	10.5
	28	16.0	12.0	34	12.0	14.0
	27	16.5	12.8	40	13.0	
			11.0	31	10.0	
				27	12.5	
Mean	26.7×10^{-4}	16.5×10^{-4}	10.9×10^{-4}	33.6×10^{-5}	10.6×10^{-5}	11.7×10^{-6}
Standard Deviation	4%	4%	7%	6%	9%	15%
Ratio B/K	1.10	1.15	1.06	1.21	1.40	1.47

The limitations of the only available low-brightness standard have thus far thwarted a decisive demonstration of the lower limit of radiation at which reliable brightness readings can be obtained. However, the evidence at hand indicates that such a lower limit for a dark-adapted observer is well below 400 milliroentgens per hour. This estimate is based on the following considerations. The best phosphor disc produced to date in the work described in Chapter 4 is a 2-inch disc consisting of 9.7 grams of phosphor in a polystyrene binder. Its brightness under 40 mr/hr of radium gamma excitation, as measured by a type 5819 photo-multiplier[5] was 1.2 x 10^{-6} foot-lamberts, or one-tenth of the brightness readings shown in Column F of Table 3.3-3. Hence a radiation of 400 mr/hr is certainly measurable by brightness comparison.[6] However the improvement in detection threshold and arrow orientation brought about by a decrease in the phosphor-to-eye distance as shown in Table 3.3-1 is so spectacular as to permit a confident statement that some degree of improvement can also be made in brightness comparison by the same means. Another area in which improvement is to be expected is the manufacture of larger and more efficient phosphor discs than

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5. The photomultiplier calibration against the low-brightness meter is described in Appendix A.1.

6. The linearity of brightness response of ZnCdS(Cu) with exciting intensity at room temperature over an intensity range of 10^5 has been demonstrated by Nail et al (N1).

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are now available. Stating the possible lower limit as well below 400 mr/hr therefore seems quite conservative. The upper limit of the visual radiation meter, set by the saturation brightness of the phosphor, has not been explored, but the data of Table 3.3-2 and of the figure in Appendix A.1 show that it is greater than 100 roentgens per hour. An estimate of 1000 r/hr for this figure would be conservative.

Concerning the limitations on the use of a visual radiation meter in view of the thresholds for detection and successful brightness comparisons shown above, it is evident that dark adaptation of the observer will be a pre-requisite to radiation measurements near the measurement threshold, with the required degree of dark adaptation increasing as the minimum radiation to be measured decreases. As a result, an observer originally adapted to daylight, observing continuously as his dark-adaptation progresses, will be able to see levels of radiation in the vicinity of 10 roentgens per hour within a few seconds, but will require 15 to 20 minutes of dark adaptation before he will be able to detect 20 mr/hr, or to measure the order of 100 mr/hr. Dark adaptation time can of course be greatly decreased by pre-adaptation in red light through the use of red goggles, as now extensively used by those engaged in night navigation and gunnery in the armed services. Hulbert (H1) has shown that, while essentially complete dark

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adaptation requires 21 minutes after exposure to 120 foot-candles of tungsten light, the required time is reduced to 7 minutes after exposure to the same intensity of red light (6500 A°).

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CHAPTER 4

LUMINESCENT MATERIAL IN PLASTIC BINDER

4.1. Phosphor-Plastic Mixtures.

The selection of a sulfide phosphor for use in the visual radiation meter was followed by a search for means to obtain the maximum brightness at the surface of a layer of phosphor. A review of the literature and inquiry among persons and companies interested in crystal growing revealed no source of zinc sulfide crystals of reasonable size, so attention was turned to improving the luminescent yield of the fine-grained zinc-cadmium sulfide which appeared to be the best readily obtainable phosphor for our purpose (Section 3.2).

The chief limitations on the light output from the surface of a given mass of this material and of the zinc sulfide phosphor family in general, arise from their small crystal size (1-50 microns), strong absorption of their own emitted light, and high index of refraction (for ZnS, $n = 2.356$, and for CdS, $n = 2.506$, both at 5893 A^{o}, (H2)). Thus in thick layers of these small crystals, scattering of the light emitted from an interior crystal increases the probability of absorption before it reaches the surface where it can be seen. Furthermore, the high index of refraction and consequent small critical angle $\sin^{-1} \frac{1}{n}$ for total internal

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reflection at a crystal-air surface, mean that a large fraction of the light must make one or more reflections from a crystal-air surface before escaping from the crystal, hence absorption in this manner may also seriously reduce the potentially available light. (The crystals of several sulfide phosphors examined do not have perfectly regular shape, but have small striations on the crystal faces, so it is unlikely that a significant portion of the light would be permanently entrapped in the crystals due to internal reflection.) Thus it seemed reasonable that we might improve the total light output at the surface of a given mass of phosphor by simply filling the interstices between crystals with a material of refractive index matching or approaching that of the phosphor, provided such material is transparent to the emitted light. Thus we would at once increase the critical angle at the crystal surfaces, since it is given by $\sin^{-1}(n'/n)$ (where n' is the refractive index of the less dense and n of the more dense medium), allowing a larger fraction of the generated light to escape from a crystal without total internal reflection, and decrease the reflection coefficient at each crystal boundary, since this coefficient depends, at normal incidence, on $(n'-n)^2/(n'+n)^2$.

A transparent plastic immediately suggests itself as a possible binder for the phosphor crystal powder. The use for other purposes of a transparent plastic binder for powdered crystalline sulfide phosphors has been reported pre-

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viously. Frey (F1) used a thin paste of zinc sulfide and polystyrene spread directly on the envelope of an end-window photo-multiplier to count neutrons by luminescence of the zinc sulfide excited by recoil protons from the plastic. Robinson and co-workers (R1, R2) have used similar thin mixtures of several inorganic phosphors and polystyrene to count alpha particles. Considerable attention has been given lately (S2, K3) to the use of organic phosphor materials dissolved in plastics of various kinds, obtaining large, clear, amorphous masses for counting neutrons and gamma-rays with high efficiencies at high counting rates.

We are here interested, however, in finding the optimum thickness, in grams per square centimeter, and the optimum proportion of plastic and phosphor, which will yield the brightest surface luminescence under gamma excitation, points on which little information has been available. Kallman (K2) has published curves showing total light output from phosphor screens as a function of thickness, under alpha and gamma excitation. His curve for α-excitation is reproduced as Figure 4.1-1, where it is seen that the maximum light intensity from ZnS, Zn_2SiO_4, and $CaWO_4$ occurs at 5 mgm/cm^2, which according to Kallman is just the range of the alpha-particles used. Under gamma excitation, Figure 4.1-2, the light intensity does not appear to reach a maximum for any of these phosphors, but flattens out above 50 mg/cm^2, increasing only slightly for greater thicknesses. Kallman notes that this effect demon-

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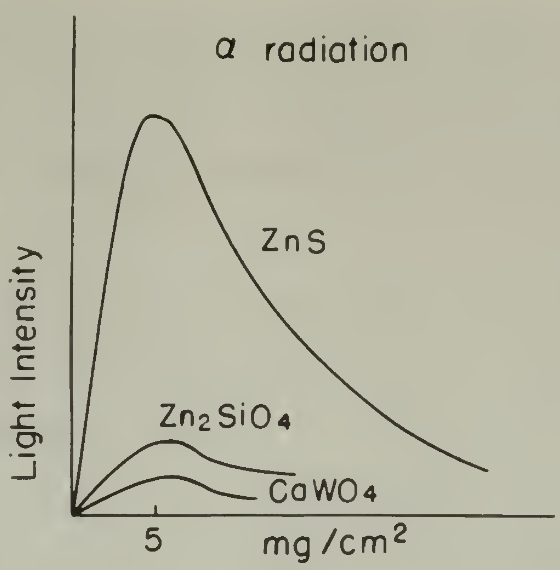

Figure 4.1-1 LUMINESCENT LIGHT INTENSITY AS A FUNCTION OF PHOSPHOR THICKNESS. ALPHA EXCITATION. (Kallman, Ref. K2)

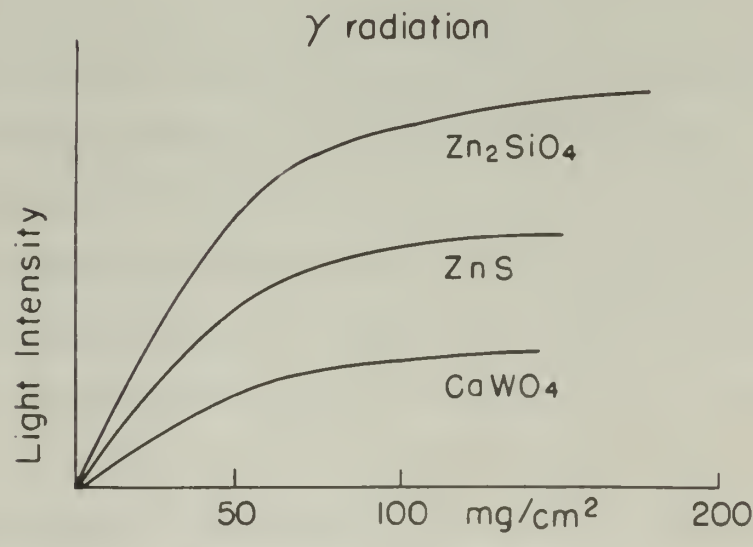

Figure 4.1-2 LUMINESCENT LIGHT INTENSITY AS A FUNCTION OF PHOSPHOR THICKNESS. GAMMA EXCITATION. (Kallman, Ref. K2)

strates that these materials do absorb the emitted light, since the gamma radiation used was sufficiently hard that no appreciable absorption of the gammas took place in the phosphor.

(The relative light outputs of Zn_2SiO_4 and ZnS under alpha and gamma excitation as shown appear to be incompatible. Generally, it would be expected that relative efficiencies of two phosphors would not change greatly under different excitation. Such a view is supported by efficiency data on these two phosphors published by Kallman in two different reports (B1, K2), showing that the sulfide is more efficient than the silicate under α, γ, and x-ray excitation, and by the experimental results reported in Section 3 of this chapter. Hence it is reasonable to suspect that the labels of the curves for Zn_2SiO_4 and ZnS in Figure 4.1-2 have been interchanged by error.)

These curves by Kallman furnish an additional reason for using a plastic binder for the powdered phosphor. Since we are interested in maximum brightness of the phosphor surface, under gamma-ray excitation, we evidently must use thicknesses of sulfide phosphor greater than 0.1 mg/cm^2 (Figure 4.1-2, curve for ZnS). The plastic binder appears to be a convenient means of obtaining a homogeneous surface in such large thicknesses, provided no loss of brightness results from introduction of the plastic.

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4.2. Manufacture of Phosphor-Plastic Mixtures.

Selection of the plastic materials for use in these experiments was necessarily based on their working properties and availability as well as their optical properties. The plastics finally selected were a methacrylate[1] (Lucite) and a polystyrene[2], with refractive indices (in yellow light) of 1.50 and 1.59 respectively, the latter being relatively high among the transparent plastics. The lucite was obtained in the form of a compression-molding powder, the polystyrene as a monomer casting liquid, polymerized by heating after the addition of a small amount of catalyst (benzoyl peroxide with 6% active oxygen) and an accelerator (methylene chloride). Both these plastics are nearly transparent in the visual range (R6), with a transmission greater than 85% in the emission bands of Zn-CdS(Cu) and Zn_2SiO_4 (Mn) (Figures 3.2-1, 2).

The first experiments were made with the polystyrene casting liquid. The technique used for manufacturing discs of any desired phosphor-plastic proportion is a simple one briefly described as follows:

Weigh into a glass mold the desired amount of casting liquid and add one drop of catalyst for each 3 grams of plastic. Stir vigorously with glass rod to distribute the catalyst. Add the desired weight of phosphor by sprinkling

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Weigh into a glass mold the desired amount of casting liquid and add one drop of catalyst for each 7 grams of plastic. Stir vigorously with glass rod to distribute the catalyst. Add the desired weight of phosphor by sprinkling

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it over the surface of the casting liquid and stir until a uniform paste is obtained. Add 1 drop of accelerator per 3 grams of plastic and stir again to distribute the accelerator (a slightly larger proportion of accelerator may be necessary for mixtures with a phosphor to plastic weight ratio of 2 or higher). Allow to stand for about 10 minutes at room temperature, then place in oven at 92°C for about 1 hour (longer for large phosphor/plastic ratios). Cool slowly to room temperature. The mixture contracts slightly upon solidifying so that it can readily be removed from the mold.

The discs so obtained when glass culture dishes were used as molds had a glossy top surface, but the bottom and sides in contact with the glass during molding had a dull finish which could be polished on a metallographic specimen polishing wheel. The principal defect of the discs so prepared was that the phosphor/plastic ratio was not uniform through a cross-section, the heavy sulfide powder having a marked tendency to settle to the bottom of the mold through the viscous liquid. This effect introduced an uncertainty regarding the effective phosphor/plastic ratio at the top and bottom surfaces when the total light output was to be measured in a series of discs with varying overall proportions of phosphor to plastic. For this reason we turned to the use of lucite molding powder with which it was found that

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quite homogeneous discs can be made at ratios less than 3.0 if sufficient attention be paid to the mixing in the procedure described below. This virtue of the lucite powder was considered to offset the disadvantage of its smaller index of refraction at least for the purpose of determining the optimum phosphor/plastic ratio; as will be seen later a polystyrene mixture produced the most efficient phosphor disc.

The lucite-phosphor mixtures were molded under pressure supplied by a small hydraulic press designed for embedding metallographic specimens in plastic. The first phosphor discs were made in a 1" diameter mold but for visual observation a larger size was desirable, and a 1 7/16" mold was used for all the later work.[3] The mold consists of a cylindrical steel sleeve with wall designed to withstand 5000 Psi, closed at the bottom by a removable steel plug, and at the top by a steel plunger through which the pressure was applied. A hole was drilled through the plunger to within 3/8 in. of the bottom, to receive a thermometer. The bottom plug and the plunger fit the sleeve with a tolerance of 0.001 inch to prevent appreciable extrusion between the moving parts, and all inner surfaces of the mold were ground to a smooth finish. To heat the mold, a heating jacket was made consisting of a cylindrical aluminum shell with inner diameter fitting the

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steel sleeve of the mold loosely. A coil of nichrome wire, insulated with asbestos, was wound inside the shell as the heating element. With this equipment, the following procedure was used in making phosphor-plastic discs:

Weigh the desired amounts of phosphor and plastic onto weighing paper. Mix thoroughly with spatula. After cleaning all inner surfaces of the mold with alcohol or acetone, pour the plastic-phosphor mixture into mold with bottom plug in place, and mix again in the mold. Insert plunger, place assembled mold in press and apply 100 psi to remove air. Release pressure, heat to 110°C; apply 3000 psi, heat to 140°C. Cool rapidly to 90°C, force out plunger and plug with completed phosphor disc.

This procedure produced homogeneous phosphor-plastic discs with ratios up to 3.0. At larger ratios it was difficult to prevent inhomogeneities, and beyond 4.0 the surfaces invariably showed local areas containing little or no plastic so that the phosphor was easily chipped off. At ratios below 3.5 the surfaces were ordinarily smooth and well-polished. In all, about 65 discs were made with this procedure, though only about half of these were of value in obtaining the results of the next section.

4.3. Experiments with Phosphor-Plastic Mixtures.

(a) Experimental Equipment.

The point of departure for the phosphor-plastic

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(a) <u>Experimental Equipment.</u>

The point of departure for the phosphor-plastic

mixture experiments was to determine the thickness of phosphor alone which would provide the greatest light yield under gamma and beta excitation. For this purpose, and for phosphor disc measurements, equipment was arranged to measure the brightness of a phosphor screen on one surface while the exciting radiation was applied to the opposite surface, following the procedure used by Kallman (K2).

A Type 5819 photomultiplier tube was mounted in a brass light shield with a cardboard (0.13 gm/cm^2) light-tight top which was readily removable for easy access to the end-window. The tube was protected with a magnetic shield, and operated at 75 volts per dynode from a stabilized negative high-voltage supply. Anode current from the 5819 tube was measured by a Beckman micro-microammeter for currents up to 10^{-7} amperes, and by a Beta microammeter for larger currents.

The stability of this system was such that a reference current reading, established early in the work, consisting of a reference phosphor disc excited by a small radium source placed at a fixed distance from the phosphor, could be repeated at will within less than 4% over a period of seven weeks. Provision was made for adjusting the photo-multiplier voltage to compensate for changes in the reference reading due to drift, line voltage changes, etc., but this was necessary on only two occasions. Under these conditions of photomultiplier operation, fatigue effects and noise current were

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The stability of this system was such that a reference phosphor reading, established early in the work, consisting of a reference phosphor disc excited by a small radium source placed at a fixed distance from the phosphor, could be repeated at will within less than 1% over a period of seven weeks. Provision was made for adjusting the photo-multiplier voltage to compensate for changes in the reference reading due to drift, line voltage changes, etc., but this was necessary on only two occasions. Under these conditions of photomultiplier operation, fatigue effects and noise current were

not noticeable. The arrangement described was used for all phosphor light output measurements reported in this chapter. Conversion of photo-multiplier anode current to an approximate figure for phosphor brightness in foot-lamberts was accomplished by the calibration procedure described in Appendix A.1.

(b) Light Yield of Phosphor Powder.

The phosphor powder was placed in a cylindrical aluminum cell with thin glass bottom resting directly on the end-window of the phototube. The inside diameter of the cell was 1.406 inches, slightly less than the minimum specified diameter (1.5 inches) of the photo-cathode, and closely matching the diameter of the most frequently used size of phosphor-plastic discs, 1.436 inches. (Care was taken to place the cell and the discs in a constant position on the cathode, and a 1.5 inch mask on the end-window was used as a guide for this purpose. Anode current reading is not critical for variations in placement of less than 0.1 inches.) The phosphor was irradiated by a 10 mg. (8.8 mrhm) radium gamma source (calibrated by the Bureau of Standards) placed at 45 cm from the face of the cathode. Current response of the phototube as a function of source distance followed an inverse square law at distances greater than about 30 cm from the phototube, hence the gamma radiation at the phosphor was equivalent to approximately

$$8.1 \times \frac{10^4}{(45)^2} = 40 \text{ mr/ hr.}$$

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$$8.1 \times \frac{10^4}{(45)^2} = 40 \text{ mr/ hr.}$$

The light yield of two phosphor materials as a function of thickness under these conditions is shown in Figure 4.3-1. For Zn-CdS(Cu), the maximum yield is reached at 0.9 gm/cm^2 of phosphor, decreasing slowly at greater thicknesses due to gamma ray absorption in the upper layers of phosphor. The general shape of the Zn_2SiO_4 curve is the same, but due to its much smaller efficiency and the opacity of the crystals to the emitted light, the maximum light yield is less than one-fifth that of the sulfide and occurs at much smaller thickness.

A similar experiment using beta-ray excitation from a strontium-90 source produced the curves shown in Figure 4.3-2, where the opacity and smaller efficiency of the orthosilicate produce effects relative to the sulfide similar to those found under gamma excitation. The peak light yield occurs in Zn-CdS(Cu) at about 0.2 gm/cm^2. If to this is added the absorber thickness traversed by the betas before reaching the phosphor (a total of 0.16 gm/cm^2), it is seen that the peak corresponds closely with the 0.38 gm/cm^2 range of beta particles having the average energy (0.92 Mev) of the yttrium-90 beta spectrum (E1, E3). For the Zn_2SiO_4, the maximum light yield occurs at smaller thickness because of absorption of the light emitted in the upper layers of phosphor.

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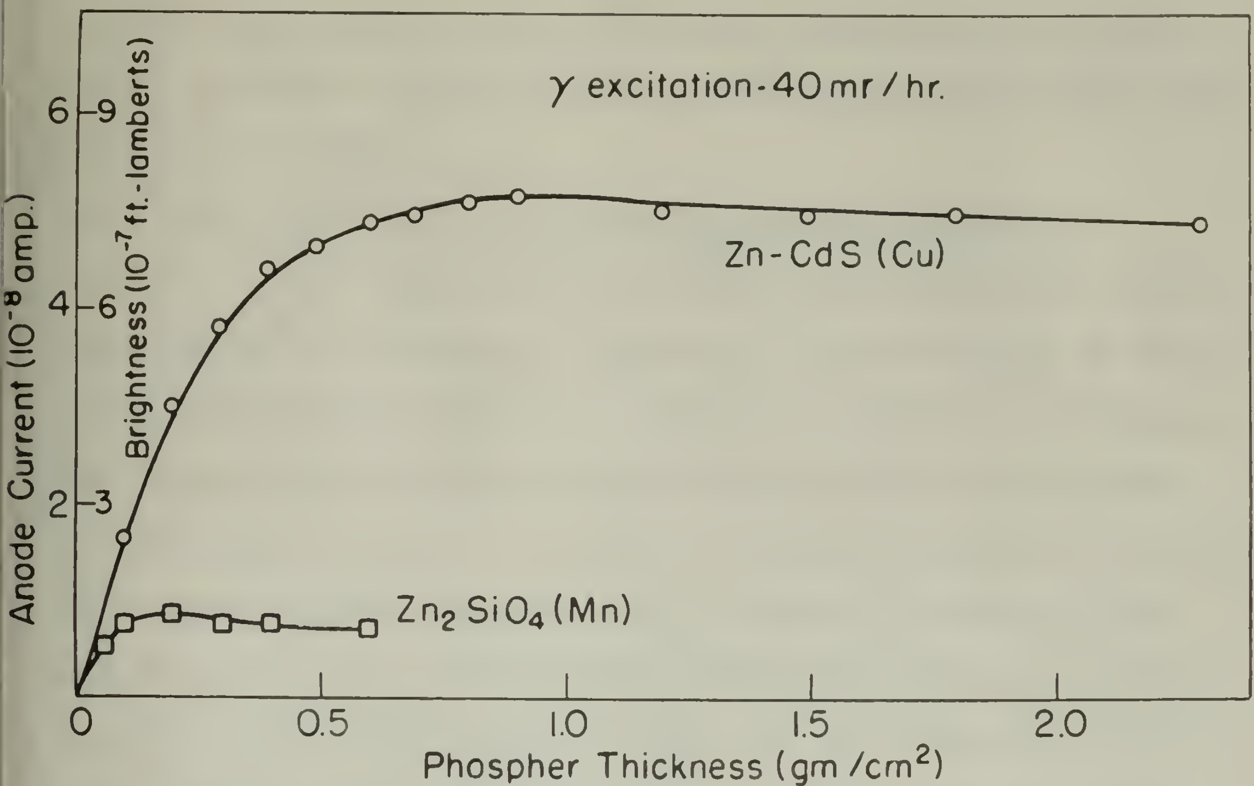

Figure 4.3-1 LIGHT YIELD AS A FUNCTION OF PHOSPHOR THICKNESS. GAMMA EXCITATION.

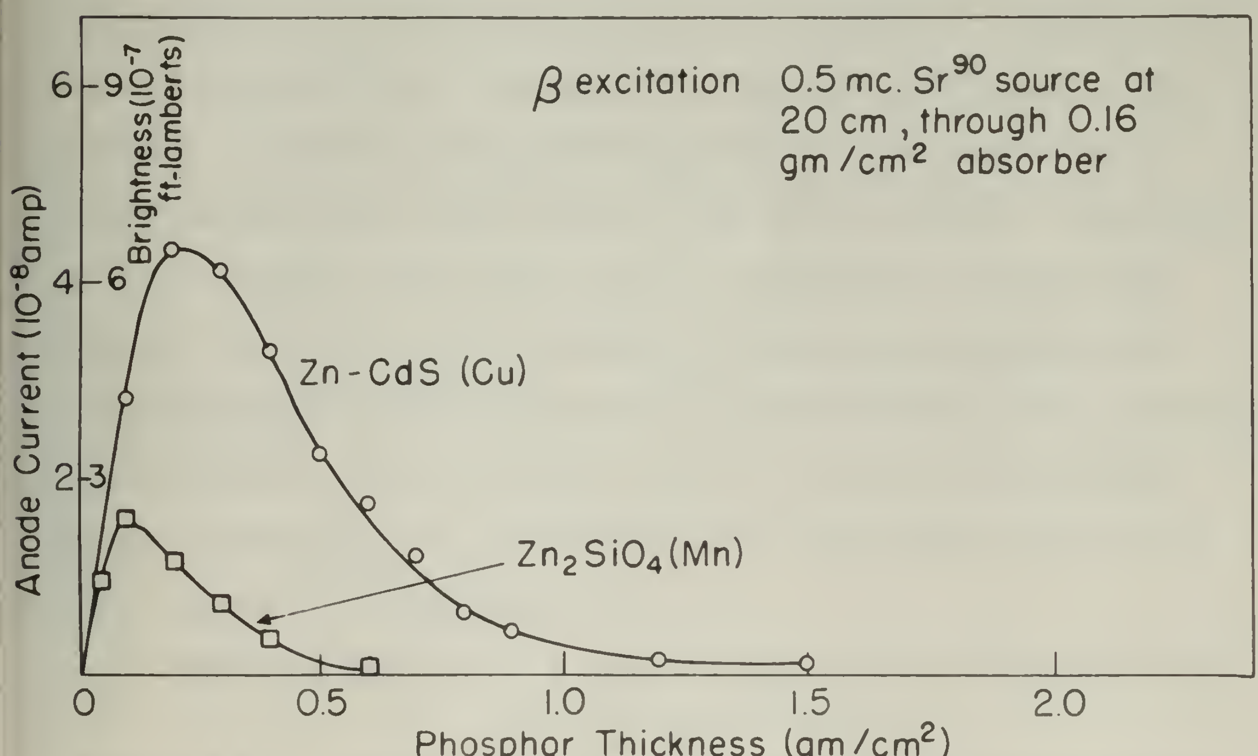

Figure 4.3-2 LIGHT YIELD AS A FUNCTION OF PHOSPHOR THICKNESS. BETA EXCITATION.

to draw comparisons, since the exact constitution and form of the phosphor screens and the sources of radiation he used were not reported.

(c) Light Yield of Phosphor-Plastic Mixtures.

The light yield as a function of phosphor thickness (gm/cm^2) is shown in Figure 4.3-3 for a series of phosphor-lucite discs containing increasing amounts of phosphor but with a constant proportion of phosphor to lucite given by the weight ratio R = 2 (grams of phosphor/grams of lucite). (The light yields plotted are the average readings of the two flat surfaces, to compensate for small inhomogeneities. The two readings ordinarily differ by less than 7%.) At small thicknesses it is seen that the light yield parallels that of the phosphor powder alone, which is re-drawn here for comparison from Figure 4.3-1, but reaches a maximum at about 0.8 gm/cm^2, and declines for greater thickness. This decline is interpreted as the result of increased loss of light emitted from the sides of the disc as linear thickness of the disc and hence area of the cylindrical surface increases, as well as the result of increased absorption of light, primary gammas, and secondary radiation by the plastic. (The response of clear lucite discs to gamma radiation has been measured and is of the order of 0.01 times that of the same weight of phosphor.)

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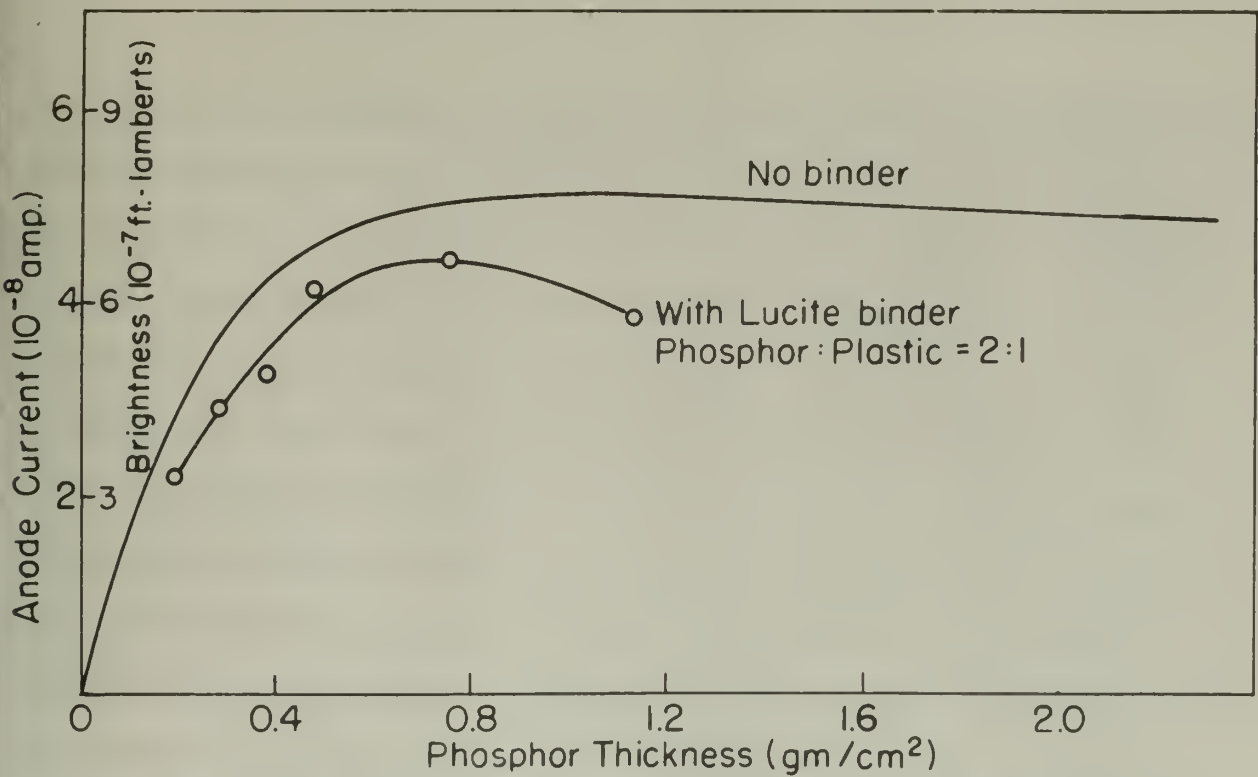

Figure 4.3-3 LIGHT YIELD AS A FUNCTION OF Zn-CdS (Cu) PHOSPHOR THICKNESS, WITH OR WITHOUT LUCITE BINDER. GAMMA EXCITATION.

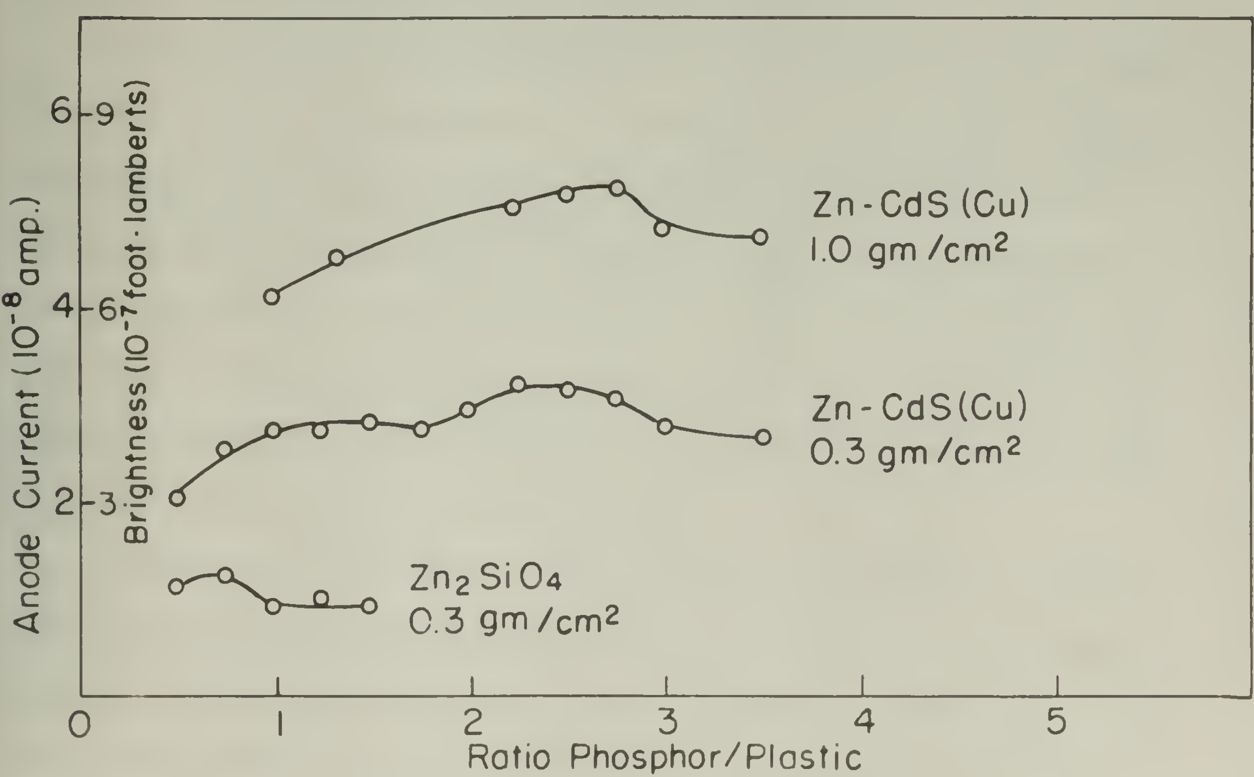

Figure 4.3-4 LIGHT YIELD AS A FUNCTION OF PHOSPHOR/ PLASTIC RATIO BY WEIGHT. GAMMA EXCITATION.

is below the optimum is shown in Figure 4.3-4, where light yield is plotted as a function of phosphor/plastic ratio R for two series of sulfide-lucite discs with constant phosphor thicknesses, showing that the optimum ratio appears to be about 2.75, for 1.0 gm/cm^2 of phosphor, and about 2.25 for 0.3 gm/cm^2. The curve for 1.0 gm/cm^2 phosphor includes the most efficient phosphor-lucite discs prepared to date, but it is noteworthy that the light yield from the best of these is slightly but not significantly higher than the maximum reached with the phosphor powder alone. We can say only that, at the optimum ratio and thickness (R = 2.75, thickness 1.0 gm/cm^2) found to date, the additional light which is brought to the surface by the lucite binder is nearly offset by the other effects mentioned above.

Also shown in Figure 4.3-4 is a curve for Zn_2SiO_4 with constant phosphor thickness 0.3 gm/cm^2. The maximum light output at R = 0.75 is about 40% greater than the maximum obtained from the phosphor alone as shown in Figure 4.1-1. At ratios greater than 1.5 there is insufficient lucite to bind the very fine phosphor powder together. In view of the poor efficiency of this material compared to the sulfide, no further work with it was undertaken.

Turning to the use of polystyrene, which has a larger index of refraction than lucite, we have found a remarkable improvement over the performance of lucite, as indicated by the results in Table 4.3-1. The table gives the thickness

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TABLE 4.3-1

POLYSTYRENE AND Zn-CdS(Cu) MIXTURES

No.	Phosphor Thickness (gm/cm^2)	Overall Ratio Phosphor/Plastic	Anode Current (10^{-8} amperes) and 1 1/2 inch diameter surface. top face	bottom face
1	0.29	0.58	5.0	5.3
2	0.49	2.85	8.0	6.95
4	0.61	3.75	6.60	6.55

In the case of the polystyrene discs, as mentioned previously, a means of ensuring that the phosphor and plastic remain homogeneously mixed in the finished product has not yet been worked out. For this reason, the top surface of

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1	0.29	0.58	5.0	5.3
2	0.49	1.95	6.0	6.95
4	0.61	3.73	6.30	6.53

In the case of the polystyrene discs, as mentioned previously, a means of ensuring that the phosphor and plastic remain homogeneously mixed in the finished product has not yet been worked out. For this reason, the top surface of

disc No. 1 listed in Table 4.3-1 is almost clear plastic, the bottom being greatly enriched in phosphor. As a result, it might be anticipated that the brightness reading of the top surface would be smaller than that of the bottom (excitation in each case being directed at the opposite face, as usual), because the effective phosphor/plastic ratio at the bottom is closer to the optimum ratio, and the readings confirm this. In No. 2, the smaller proportion of polystyrene prevented as large a phosphor density gradient from bottom to top as shown by No. 1, but the bottom is definitely richer in phosphor than the top, and it is the top surface of No. 2 which yields the largest brightness reading, under the standard excitation (gamma radiation, 40 mr/hr) of all the phosphors tested. Since the overall ratio of phosphor to plastic in the disc is very close to the optimum ratio found for lucite mixtures with the same phosphor (Figure 4.3-4 upper curve), it follows that the effective ratio at the bottom surface is greater than the optimum, while the effective top ratio is less than optimum. Thus the upper region of this disc, where the phosphor crystals are relatively more widely spaced, makes its contribution to the high surface brightness and also permits efficient transmission of the light generated in the interior region of optimum ratio to the top surface, while the region near the bottom has the crystals too closely packed to permit such efficient transmission and furthermore its higher than optimum ratio of

phosphor to plastic means that it is in the region of R = 3 or higher, where its light yield is sharply below that of the optimum, a characteristic shown by all three curves of Figure 4.3-4. Finally, inspection of disc No. 4(No. 3 is a clear plastic control disc) with an overall ratio much higher than the optimum, shows that it has a density gradient that is smaller than that of No. 2, but still perceptible. It is therefore unlikely that the effective ratio of phosphor to plastic at the top could be at or below optimum, and this is borne out by the brightness readings as shown.

The better performance of polystyrene as a binder, as compared to lucite, must be attributed largely if not entirely to its higher index of refraction, more closely approaching that of the sulfide phosphor. The polystyrene itself does not make an appreciable contribution to the light yield of the discs, as is shown by the yield of a transparent control disc of polystyrene, manufactured concurrently with No.'s 1 and 2. This disc gives a response under the standard gamma excitation only 0.03 times the reading of No. 1 which contains a comparable amount of plastic. (There remains the remote possibility that the polystyrene is excited to luminescence by the emission spectrum of the phosphor.)

4.4. Recommendations for Future Work.

The visual radiation meter described in Chapter 3 is certainly realizable in its present form but is subject to

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Although the objective of the work on phosphor-plastic mixtures, namely to obtain more usable light from a given amount of phosphor incorporated in such a mixture than could be obtained with the same mass of phosphor alone, has been attained to a degree which will be useful in the visual radiation meter, there are many directions in which further and probably greater improvements can be sought. A thorough search should be made for more efficient phosphors and for workable transparent plastics with higher refractive indices. In the absence of such plastics, experiments with liquids of high index might indicate what could be done if comparable plastics or other solid binders were available.

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The individual curves of Figures 4.3-1 through 4.3-4 can be regarded as profiles of a three-dimensional surface which may be represented graphically if light yield is plotted along the z-axis, and the x- and y-axes are scaled in grams per square centimeter of plastic and phosphor respectively. Straight lines in the x-y plane, passing through the origin, then represent lines of constant phosphor/plastic ratio. Systematic exploration of such a surface for a given phosphor-plastic system, plotting contours of constant light yield, might lead to a fuller understanding of the effects of mixing plastic with phosphor.

APPENDIX A.1

PHOTOMULTIPLIER CALIBRATION

In order to evaluate the visual effect of the light yield from phosphors without subjecting the experimenter to unnecessary radiation dosage, it became desirable to translate the 5819 photomultiplier anode current response to luminescence into a unit of brightness. The means of accomplishing this is as indicated in Figure A.1-1. The phosphor, excited by ultra-violet light, was viewed first by two observers using the Low-Brightness Meter, and then by the photomultiplier, as phosphor excitation was varied by interposing increasing thicknesses of U-V absorbing glass plates.[1] As shown in the figure, phosphor brightness and photomultiplier current are proportional as intensity of excitation varies over a range of 200 times the lowest brightness at which reliable readings could be made with the Low-Brightness Meter. The proportionality factor thus obtained (1.5×10^{-5} foot-lamberts per micro-ampere) applies, of course, only to the particular emission spectrum (that of Zn-CdS(Cu)), size of phosphor (1 7/16 in.), and photomultiplier tube used in the calibration.

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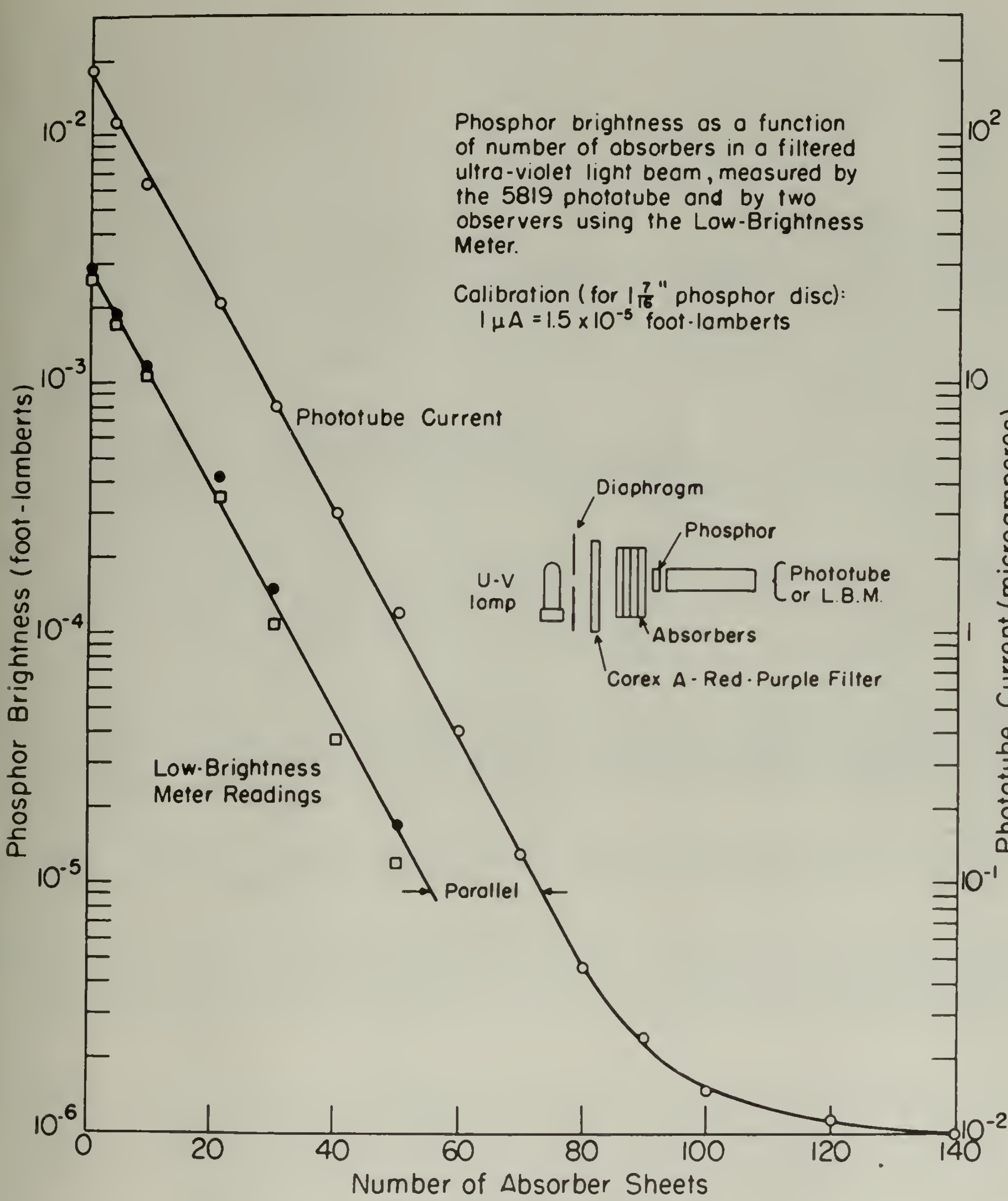

Figure A.1-1 PHOTOTUBE CALIBRATION

APPENDIX A.2

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APPENDIX A.3

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APPENDIX A.1

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